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# On the concept of e-maintenance: Review and current research

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**Abstract**

The importance of the maintenance[1] function has increased because of its role in keeping and improving system availability and safety, as well as product quality. To support this role, the development of the communication and information technologies has allowed the emergence of the concept of e-maintenance. Within the era of e-manufacturing and e-business, e-maintenance provides the opportunity for a new maintenance generation. As we will discuss later in this paper, e-maintenance integrates existing telemaintenance principles, with Web services and modern e-collaboration principles. Collaboration allows to share and exchange not only information but also knowledge and (e)-intelligence. By means of a collaborative environment, pertinent knowledge and intelligence become available and usable at the right place and time, in order to facilitate reaching the best maintenance decisions.

This paper outlines the basic ideas within the e-maintenance concept and then provides an overview[2] of the current research and challenges in this emerging field. An underlying objective is to identify the industrial/academic actors involved in the technological, organizational or management issues related to the development of e-maintenance. Today, this heterogeneous community has to be federated in order to bring up e-maintenance as a new scientific discipline.


*Keywords:* Maintenance; E-maintenance; Monitoring; Diagnostic; Prognostic; Decision support

## 1. Introduction

The term e-maintenance has emerged since early 2000 and is now a very common term in maintenance-related literature. However, we do believe it is not yet consistently defined in nowadays maintenance theory and practice. Engineers or scientists may consider e-maintenance as a concept, or as a philosophy, or as a phenomenon, and so on. For instance, according to Baldwin [2] the "e" in e-maintenance means "excellent":

E-maintenance = Excellent maintenance
= Efficient maintenance (do more with fewer people and less money)
+ Effective maintenance (improve RAMS metrics)
+ Enterprise maintenance (contribute directly to enterprise performance) [2].

Nevertheless, the concept of e-maintenance that is widespread today in the industry refers to the integration of the information and communication technologies (ICT) within the maintenance strategy and/or plan [3] to face with new needs emerging from innovate ways for supporting production (e-manufacturing), business (e-business) … expected by the Manufacturing Renaissance [4]. But let us first discuss this point: may we consider e-maintenance a maintenance strategy (i.e. a management method), a maintenance plan (i.e. a structured set of tasks),

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[1]The maintenance terminology used in this paper is extracted from the European standard *EN 13306:2001 de/fr/en European Standard on Maintenance Terminology*.

[2]Last year, within a current research project called "Modelling policies for the improvement of production systems dependability" (Project number DPI 2004-01843) and sponsored by the Spanish government, we have launched a call for paper on e-maintenance to better understand the nature and the impact of the e-maintenance phenomenon. The results were presented in different conferences and some of them are published within a special issue on e-maintenance for Computers in Industry, Guest Editors B. Iung and A. Crespo Marquez [1].

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a maintenance type (such as condition-based maintenance (CBM), corrective, etc.) or a maintenance support (i.e. resources, services to carry out maintenance)? We can find some clues to answer this question in the following paragraphs:

- *E-maintenance as a maintenance strategy*: E-maintenance can be merely defined as a maintenance strategy where the tasks are managed electronically using real-time equipment data obtained thanks to digital technologies (i.e. mobile devices, remote sensing, condition monitoring, knowledge engineering, telecommunications and Internet technologies) [5]. From this point of view, e-maintenance is interpreted as a maintenance management process [6], which deals with the expansion of the volume of data available. This definition is refined by Baldwin [7] or by Moore and Starr [52] in the following way: "E-maintenance is an asset information management network that integrates and synchronises the various maintenance and reliability applications to gather and deliver asset information where it is needed when it is needed".
- *E-maintenance as a maintenance plan*: E-maintenance can also be seen as a maintenance plan, which meets the needs of the future e-automation manufacturing world in the exploration of the approaches of CBM, proactive maintenance, collaborative maintenance, remote maintenance and service support, provision for real-time information access, and integration of production with maintenance [8]. The implementation of an e-maintenance plan requires a proactive e-maintenance scheme, i.e. an interdisciplinary approach that includes monitoring, diagnosis, prognosis [9,10], decision and control processes.
- *E-maintenance as a maintenance type*: Generally speaking, e-maintenance is the symbol of the gradual replacement of traditional maintenance types [11] by more predictive/proactive types. Regular periodic maintenance should be advanced and shifted to the intelligent maintenance philosophy to satisfy the manufacturer's high reliability requirements [12]. Hence, Koç and Lee [13] referred e-maintenance (system) as predictive maintenance (system), which provides only monitoring and predictive prognostic functions (Fig. 1) [15].
- *E-maintenance as a maintenance support*: Last but not the least, e-maintenance can be referred as a maintenance support. For example, Zhang et al. [16] consider that e-maintenance is a combination of Web service technology and agent technology, which provides a way to realize intelligent and cooperative features for the systems in an industrial automation system. Crespo Marquez and Gupta [17] define e-maintenance as a distributed artificial intelligence environment, which includes information processing capability, decision support and communication tools, as well as the collaboration between maintenance processes and expert systems.

After all this conceptual review, our idea is to propose an e-maintenance definition that on the one hand takes into consideration the European Standard (EN 13306:2001) for maintenance terminology, and on the other hand understands e-maintenance as a component of the e-manufacturing

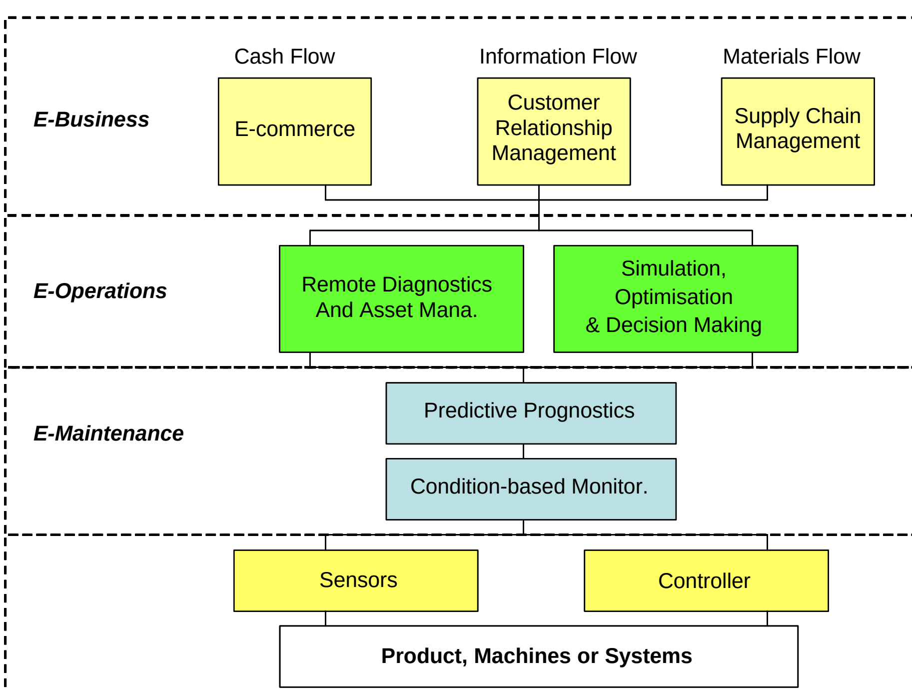



Fig. 1. An enterprise view of e-maintenance [14].

concept[3] [18], which benefits from the emerging information and communication technologies to implement cooperative and distributed multi-user environment [19]. According to this we proposed the following e-maintenance definition:

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

Following this introduction, Section 2 outlines the reasons why the concept of e-maintenance has emerged recently. We will see later on how the main reasons for this are related to the new capabilities provided by e-maintenance technologies. The said capabilities are thus described in Section 3 according to their impact on the concerned maintenance types and strategies, maintenance support and tools, and finally maintenance activities. However, although the e-technologies provide certain capabilities, maximizing the e-maintenance benefits for the overall maintenance efficiency requires more than technology. As depicted in Section 4, it needs models, methods or methodology in order to make e-maintenance a key element to satisfy operational requirements and to improve the global production system performance. From this dual perspective "capabilities and needs", Section 5 presents a state of the art of the e-maintenance field. The contributions are classified according to the capabilities and the needs which are intended to be responded (Table 1). In Section 6 the impact of e-maintenance to the application of existing maintenance theory is presented. Finally, a review and conclusions are developed in Section 7.

*NB*: In addition, an e-maintenance terminology guide is provided at the end of the paper.

## 2. E-maintenance factors of emergence

The e-maintenance emergence can be attributed to two main factors:

- the appearance of e-technologies allowing the increase of maintenance efficiency, velocity, proactivity, and so on to optimize maintenance-related workflow;
- the need to integrate business performance, which imposes to the maintenance area the following requirements: openness, integration, and collaboration with the other services of the e-enterprise.

[3]E-manufacturing is a transformation system that enables the manufacturing operations to achieve predictive near-zero-downtime performance as well as to synchronize with the business systems through the use of web-enabled and tether-free (i.e. wireless, web, etc.) infotronics technologies [18].

### 2.1. E-technologies for maintenance improvement

At present, e-technologies start to play a crucial role to support maintenance decision-making. The combination of modern information processing and communication tools offers the technical support required to access remote information. Indeed it is easier to transfer information, system, and environment knowledge to different maintenance specialists in order that they could interoperate together through remote exchange [37]. Thus, it provides manufacturing companies with the ability to design new solution of distributed vs. intelligent maintenance system.

To begin with, the Web allows universal access by having independent connectivity for different kinds of platforms using open standards for publishing, messaging, and networking. Since the Web enables multi-media support, both interactivity and extensibility, it can seamlessly include new forms of content and media [47]. The developments in database and object technologies enable users to connect to back-end databases and legacy applications via user-friendly Web interfaces. The future smart transducer will have a built-in Ethernet module and support direct plug-and-play on the Internet without the need for a connection to a PC or having a separate Ethernet card, as is the case with today's systems.

Next, wireless technology in industry [53] brings cost reduction (no wiring), flexibility in manufacturing floor layout, and information availability [8]. Remote data transmitting, monitoring and controlling through the network are facilitated by tether-free technologies, computerized data processing, remote sensing, and wide-band communication. It enables the equipment in factory to share its data, files, and even permit remote-equipment operation from anywhere in the world [54].

The gate to new interconnected system abilities is open. New ways of communication means, mobile terminals, and data access modes to improve cooperation possibilities. Mobility inside the cooperative system is for example a major contribution which allows users to work together in new places [31].

In summary, e-technologies increase the possibilities (1) to utilize data from multiple origin and of different type, (2) to process larger volumes of data and to make more advanced reasoning and decision-making, and (3) to implement cooperative (or collaborative) activities. The implementation of these e-technologies to the benefit of the maintenance area is the first reason for the emergence of e-maintenance.

### 2.2. Maintenance, a key element of the e-enterprise[4]

After having optimized the different services of the enterprise, essentially thanks to computer science and the

[4]The e-enterprise, a combination of "point-and-click" net business models and traditional "brick-and-mortar" assets, is transforming business in the 21st century. These next-generation organizations share

Table 1
Positioning of some contributions related to the e-maintenance field

| E-maintenance issues/topics | State of the art contributions | Capabilities | | | | Needs | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Remote maintenance | Collaborative maintenance | Predictive maintenance | Knowledge capitalization | Security/ reliability of data | Intero-perability | Maintenance integration | Collaboration /MAS | Processes formalization | Knowledge management |
| 1. *Standards* | | | | | | | | | | | |
| MIMOSA | [20,2] | | ● | | ○ | | ● | ● | ○ | | |
| OSA-CBM | [21][22] | | | ● | ● | | ● | ● | | ○ | |
| | | | | | | | | | | ● | |
| SEMANTEC guidelines | [23] | ● | ○ | | | ● | ○ | | | | |
| Overview of standards | [24] | | | ○ | | | | | | ● | |
| 2. *Platform development* | | | | | | | | | | | |
| Literature review | [25] | ● | ● | | | ○ | ○ | ○ | ○ | | |
| IP sensor implementation | [12] | ● | | | | ○ | ○ | | ○ | | |
| Agent-based platforms | [16,3] | | ● | | | ○ | ○ | ○ | ● | | |
| ICAS (+MPROS) platform | [26,27] | ● | ○ | | | | | ○ | | ○ | |
| PHM architecture | [28] | | | ● | | | | | | ● | |
| WSDF platform | [29] | ● | ● | | | ● | ○ | ○ | ● | | |
| PROTEUS platform | [30,6] | | | | | ○ | ○ | ● | | | |
| | [31] | ● | ● | ○ | ○ | | | | ● | | |
| | [32] | | | | | | | | | | ● |
| IMS/D2B™ platform | [33,34,18] | | | ● | | | ○ | ● | | ○ | ○ |
| PROMISE project | [35,14] | | ○ | ○ | ● | | | ○ | ○ | ○ | ● |
| DYNAMITE project | [36] | ● | ● | ○ | | ○ | ○ | ○ | ○ | ○ | |
| TELMA platform | [1,38,39] | | | | | ○ | ○ | ● | ● | ○ | ○ |
| | [9,19] | ● | ● | ● | ○ | | | ○ | | ● | ○ |
| 3. *Process formalization* | | | | | | | | | | | |
| Reviews/overviews | [40,41] | | | | | | | ○ | | ● | |
| | [42,28] | | | | | | | | | ● | |
| 4. *System development* | | | | | | | | | | | |
| E-Mce system framework | [11] | ● | ● | | | | | ○ | ○ | ○ | |
| TEMIC system | [43] | ● | ● | ● | | | | | ● | ● | |
| RIMFDS system | [44] | ● | | ○ | | | ○ | ○ | ○ | ● | |
| IPDSS system | [45] | | | ● | | | | ○ | | ● | |
| Maintenance IIS | [46] | ● | | ● | | | | ○ | ○ | ○ | |
| Web-based M© system | [47] | ● | ● | | ○ | | ○ | | ● | | ○ |
| SIMAP system | [43] | | | ● | | | | ● | | ● | |
| IMS system | [13,49,15,50] | | | ● | ○ | | ○ | ● | | ● | ○ |
| DATC system | [51] | | | ○ | | | | | | ● | |
| CBC system | [52] | | | | | | | ○ | | ● | |

●, Major contribution; ○, minor contribution.

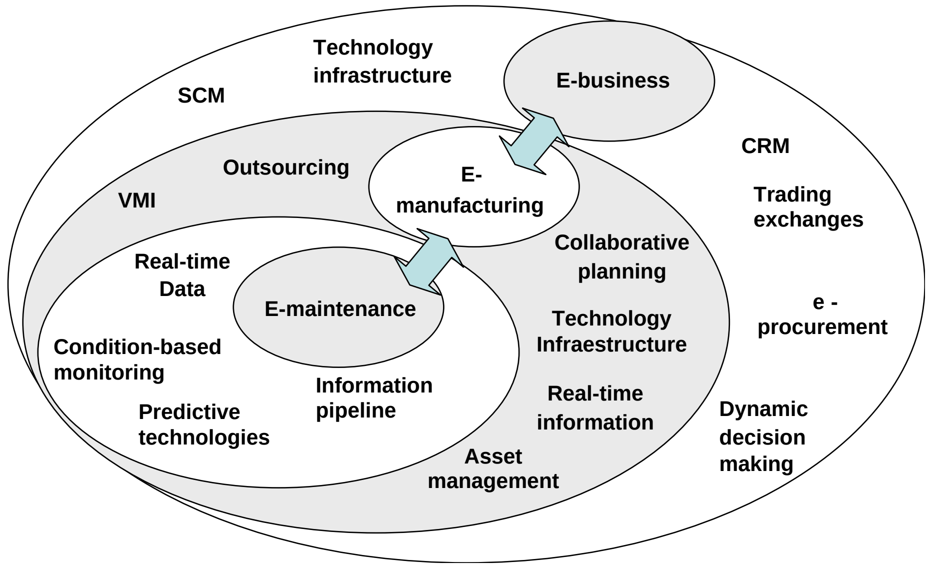



Fig. 2. Integration among e-maintenance, e-manufacturing and e-business systems [34].

different theories of automatic control and of optimization, it appeared that a global optimization needed other approaches, other theories, and other tools. The key words are then integration, computer integrates manufacturing, openness and open systems, and interoperability [30]. E-manufacturing, teleservice, and virtual enterprise are some of the first resulting concepts that have already been developed and applied in the industry [56].

Now, these requirements become more and more pressing in the maintenance area [16], due to the fact that the maintenance decisions have characters of system integration, in the sense that they are not limited to the maintenance function scope but entail co-ordination with objectives of other functions wherein a co-ordinated decision is addressed between maintenance and production [57].

At the same time, e-maintenance conforms a new approach to the production function (e-manufacturing), which is included in a new way of doing business (e-business), which itself results from a new vision of work (e-work). This spirit requires new functionalities and e-maintenance is one of them. For example, the new forms of relationships between the customers and the suppliers at the business level imply a reconsideration of the relationships between the customers and the suppliers at the maintenance level. By itself, e-maintenance is a major pillar that supports the success of the integration of e-manufacturing and e-business (Fig. 2).

The opportunity to meet the objectives of integration and global business requires more than technology. There is a clear need for new business models. According to the complexity of the concerned systems (an enterprise) and the heterogeneity of the existing models, this modelling activity has become a very complex one [30]. Providing these new models, methods, or methodology in the context of the maintenance integration is the second main reason which explains the emergence of e-maintenance.

## 3. The e-maintenance capabilities

We have identified and classified the e-maintenance advantages within the three following categories:

- maintenance type and strategies
- maintenance support and tools
- maintenance activities.

### 3.1. Potential improvements in maintenance types and strategies provided by e-maintenance

We can summarize these potential improvements as follows:

- *Remote maintenance*: By leveraging information, wireless (e.g. Bluetooth) and Internet technologies, users may log in from anywhere and with any kind of device as soon as they get an Internet connection and a browser. Any operator, manager or expert also has the capability to remotely link to a factory's equipment through Internet, allowing them to take remote actions, such as set-up, control, configuration, diagnosis, de-bugging/fixing, performance monitoring, and data collection and analysis [29]. Consequently, the

(*footnote continued*)
four key characteristics: (1) speed and real-time responsiveness to customer demand; (2) an iterative "launch, learn, and re-launch" approach; (3) holistic and rigorous methodologies to define strategy, process, application, and technology architecture; and (4) alignment of technology with the business model [55].

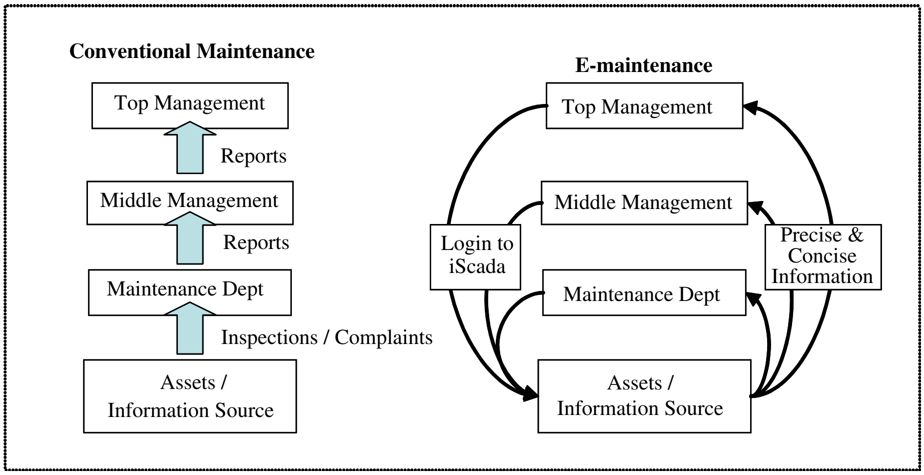



Fig. 3. Implementing e-maintenance (http://www.devicesworld.net).

manpower of the machine builder retained at the customer's site is reduced and there are facilities for him to diagnose the problems when an error occurs and, next, to improve the preventive maintenance thanks to the machine performance monitoring [56].

Actually, one of the greatest advantage of e-maintenance is the ability to connect field systems with expertise centres located at distant geographical sites [58], allowing notably a remote maintenance decision-making [17] that adds value to the top line, trim expenses, and reduce waste. The contribution to the bottom line is significant, making development of an asset information management network a sound investment [7].

Moreover, the Web enablement of computerized maintenance management systems (called as e-CMMS) and remote condition monitoring or diagnostic (called as e-CBM) avoid the expense and distraction of software maintenance, security, and hardware upgrade [5]. Computer science experts can add new features and/or migrations without the users even noticing it.

- *Cooperative*[5]*/collaborative maintenance*: E-maintenance symbolizes the opportunity to implement an information infrastructure connecting geographically dispersed subsystems and actors (e.g. suppliers with clients and machinery with engineers) on the basis of existing Internet networks. The resultant platform allows a strong cooperation between different human actors, different enterprise areas (production, maintenance, purchasing, etc.) and different companies (suppliers, customers, machine manufacturers, etc.).

An e-maintenance platform introduces an unprecedented level of transparency and efficiency into the entire industry (Fig. 3) and it can be an adequate support of business process integration [6]. As a result, there is the chance to radically reduce interfaces, may that be between personnel, departments, or even different IT systems. The integration of business processes significantly contributes to the acceleration of total processes, to an easier design (lean processes), and to synchronize maintenance with production, maximizing process throughput, and minimizing downtime costs. In general, this leads to less process errors, improved communication processes, shorter feedback cycles, and hence improved quality.

In short, e-maintenance facilitates the bi-directional flow of data and information into the decision-making and planning process at all levels [8]. By so doing, it should automate the retrieval of the accurate information that decision makers require to determine which maintenance activities to focus resources on, so that return on investment is optimized [52].

- *Immediate/on-line maintenance*: The real-time remote monitoring of equipment status coupled with programmable alerts enable the maintenance operator to respond to any situation swiftly and then to prepare any intervention with optimality. In addition, high-rate communications allow them to quickly obtain several expertises [43] and to accelerate the feedback reaction in the local loop, connecting product, monitoring agent, and maintenance support system. It has almost unlimited potential to reduce the complexity of traditional maintenance guidance through on-line guidance based on the results of decision-making and analysis of product condition [46]. For example, personal digital assistant (PDA) devices play a key role in bringing mobile maintenance management closer to the daily practice at the shop floor. The PDAs enable the maintenance personnel to directly gain information from monitored machinery.

[5]In *cooperative maintenance*, the work is cut into independent sub-tasks, every actor is responsible for a part of the resolution of the problem and the coordination is done during the assembly of partial results. While in *collaborative maintenance*, activity is synchronized and coordinated so as to build and to maintain a common vision of the problem.

In this context, potential applications of e-maintenance include formulation of decision policies for maintenance scheduling in real time based on up-to-date information of machinery operation history, machine status, anticipated usage, functional dependencies, production flow status, and so on.

- *Predictive maintenance*: The e-maintenance platform allows any maintenance strategy, and the improvement of the utilization of plant floor assets using a holistic approach combining the tools of predictive maintenance techniques is, for example, one of the major issues of e-maintenance [18].

The potential applications in this area include equipment failure prognosis based on current condition and projected usage, or remaining life prediction of machinery components. In fact, e-maintenance provides companies with predictive intelligence tools (such as a watchdog agent) to monitor their assets (equipment, products, process, etc.) through Internet wireless communication systems to prevent them from unexpected breakdown. In addition, these systems can compare a product's performance through globally networked monitoring systems to allow companies to focus on degradation monitoring and prognostics rather than fault detection and diagnostics [59].

Prognostic and health management systems that can effectively implement the capabilities presented herein offer a great opportunity in terms of reducing the overall lifecycle costs (LCC) of operating systems as well as decreasing the operations/maintenance logistics footprint [28].

### 3.2. Potential improvements of maintenance support and tools provided by e-maintenance

We can summarize these potential improvements as follows:

- *Fault/failure analysis*: The rapid development in sensor technology, signal processing, ICT, and other technologies related to condition monitoring and diagnostics increases the possibilities to utilize data from multiple origin and sources, and of different types [36]. In addition, by networking remote manufacturing plants, e-maintenance provides a multi-source knowledge and data environment [8].

These new capabilities allow the maintenance area to improve the understanding of causes to failures and system disturbances, better monitoring and signal analysis methods, improved materials, design, and production techniques [36]: to move from failures detection to degradation monitoring.

- *Maintenance documentation/record*: The e-maintenance platform provide a transparent, seamless, and automated information exchange process to access all the documentation in a unified way, independently of its origin, equipment manufacturer, integrator, and end-user (Fig. 4). Information like task completion form is filled once by user and can be dispatched to several listeners (software or humans) that registered for such events [30].

At the device level, goods are checked out from stores against a work order or a location and the transaction is

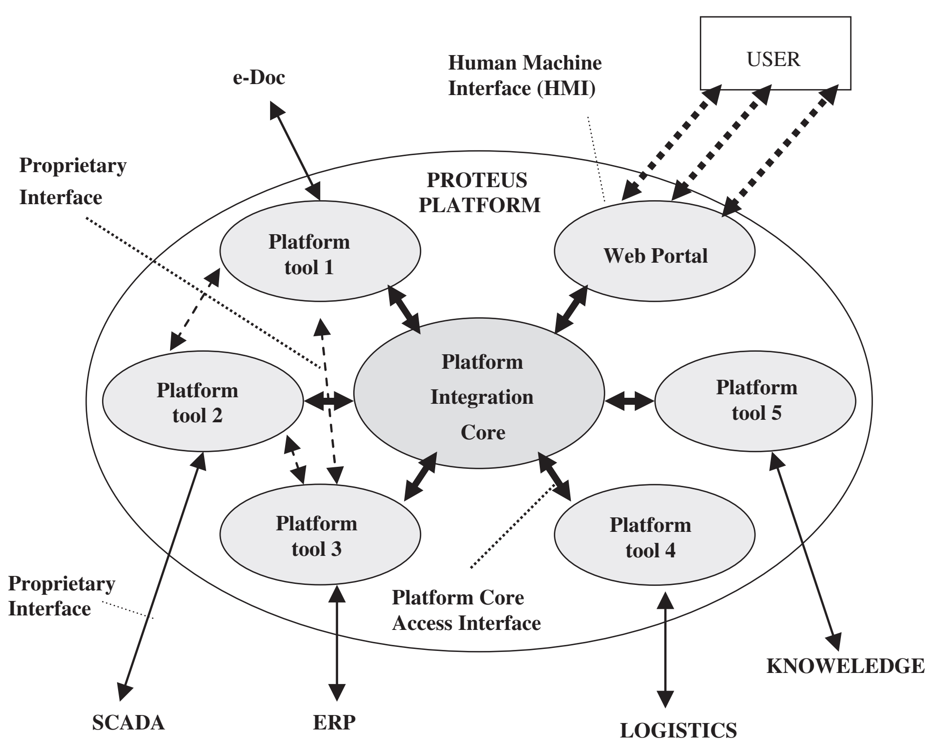



Fig. 4. PROTEUS platform [30].

recorded in real time. Then, the massive data bottlenecks between the plant floor and business systems can be eliminated by converting the raw machine health data, product quality data, and process capability data into information and knowledge for dynamic decision-making [18]. In addition, these intelligent decisions can be harnessed through Web-enabled agents and connect them to e-business tools (such as customer relation management systems, ERP) to achieve smart e-service solutions [13].

- *After-sales services*: With the use of Internet, Web-enabled and wireless communication technology, e-maintenance is transforming manufacturing companies to a service business to support their customers anywhere and anytime [15].

### 3.3. Potential improvements of maintenance activities provided by e-maintenance

We can summarize these potential improvements as follows:

- *Fault diagnosis/localization*: E-diagnosis offers to experts the ability to perform on-line fault diagnosis, share their valuable experiences with each other, and suggest remedies to the operators if an anomalous condition occurrs in the inspected machine [23]. In addition, lock-outs and isolation can be performed and recorded on location thanks to wireless technology and palm computing.

  Consequently, the amount of time it takes to communicate a production problem to the potential expert solution provider can be reduced, the quality of the information shared can be improved and, thereby, the resolution time reduced [54]. All these factors contribute to increase the availability of production and facilities equipment, reduce mean time to repair (MTTR), and significantly reduce field service resources/costs.
- *Repair/rebuilding*: For one, remote operators could via the e-connection tap into specialized expertise rapidly without travel and scheduling delays. Downtimes could conceivably be reduced through direct interaction (trouble shooting) with source designers and specialists [58]. For another, diagnosis, maintenance work performed, and parts replaced are documented on the spot through structured responses to work steps displayed on the palm top.
- *Modification/improvement—knowledge capitalization and management*: The multi-source knowledge and data environment provided by e-maintenance allows an efficient information sharing and, therefore, important capabilities of knowledge capitalization and management. With the availability of tools for interacting, handling, and analysing information about product state, the development of maintenance engineering for product lifecycle (PLC) support including maintenance and retirement stages (disassembly, recycling, reuse, and disposal) is becoming feasible [46].

## 4. Challenges for e-maintenance

As previously done for the perceived advantages of e-maintenance, we are classifying now the technological, informational, or organizational needs for e-maintenance according to their link with the maintenance type and strategies, maintenance support and tools, and maintenance activities.

### 4.1. Needs for e-maintenance related to maintenance type and strategies

We can summarize these needs as follows:

- *Remote maintenance*: There are still business- and human-related issues that have to be resolved before the actual application of remote maintenance. To begin with, an important restraining force is the security and reliability concern arising from transactions over the Internet [58]. Risk management in e-maintenance activities involves a trade-off between protection on the one hand and functionality, performance, and ease-of-use on the other [5]. Then, it is necessary to concentrate efforts on human resource restructuring, maintenance agreement, and training [56]. Each maintenance actor (technician, engineer, or leader) has to become capable of pacing with the speed of information flow and understanding the overall structure.

  Actually, a reliable, scalable, and common informatics platform between devices and business including implementation of wireless, Internet and Ethernet networks has to be developed in order to successfully implement the e-maintenance system [34].
- *Cooperative/collaborative maintenance*: The construction of an e-maintenance system involves a variety of cross-platform information integration issues, such as the development of data transformation mechanisms, the design of communication messages, the selection of data transmission protocols, and the construction of a safe network connection [29]. The goal is to develop an e-maintenance platform providing a support of e-collaboration among suppliers, design and process engineers, and as well as customers within the scope of asset management. To satisfy it, two additional requirements must be fulfilled [36]:
  - The total information flow should be structured according to a common e-maintenance semantic terminology and frame.
  - The company maintenance, economics, and business systems must be harmonized to communicate with each other and to produce the essential key figures needed for both strategic and day-to-day business decisions.

  These requirements are parts of the enterprise integration, which bas been identified by Zhang et al. [16] as the first challenge to relieve for building a platform for e-maintenance. Due to the immanently lacking efficient inter-operation among the plant software systems, research on "highly integrated" e-maintenance systems, which meet overall demands, is therefore a promising research area [3]. A successful process integration in the e-maintenance context also requires that the maintenance (logistical) processes must be stable and capable (ontology-based), i.e. the structure does not change on short-term perspective and the processes are of high quality [6].

Besides, there is a lack of cooperative systems' formal models. This is why the efficiency of cooperation within a complex computerized remote system (with several different tools, with a particular cooperation algorithm, etc.) is still a preoccupation for industrials who are users of these systems [31].

- *Distributed maintenance*: In order to successfully implement the e-maintenance system, a distributed computing, optimization, and synchronization system for dynamic decision-making needs to be developed [34]. As the e-maintenance system includes a very large volume of data, information, and knowledge, some of the more simple processing should be decentralized to a level as low as possible, e.g. to the sensor level [36].
- *Predictive maintenance*: The challenge to manage to predict failures and disturbances, and to estimate the remaining lifetime of components, mechanical systems, and integrated systems is a very tough one for the researchers and engineers [36]. Unlike numerous methods available for diagnostics, prognostic methods are still in their infancy and literature is yet to present a working model for effective prognostics. If looking at the standards and standardization proposals that exist today, it can be concluded that the sensor module, the signal-processing module, the condition-monitoring module, and the diagnostic module can all be partially developed using standards or standard means. By contrast, it is time to start focus research on the prognosis and decision support modules [24].

An effective and efficient predictive-based machine condition prognosis is necessary for modern plants [45], but it is not yet existent due to the inconsistent set of heterogeneous models used by the different designers of partial maintenance processes [60]. On this route we are today only taking the first steps. For the next steps, deepening of our knowledge in many of the technological areas involved is needed, and in addition it is necessary to find holistic approaches and methodologies to integrate the different techniques involved [36].

To support these objectives, predictive intelligence (algorithms, software, and agents) and mapping of relationship between product quality variation and machine and process degradation are required [34]. In addition, the degradation analysis has to take into account for the working environment that the machine is subjected to in its lifecycle to provide accurate predictions [12].

### 4.2. *Needs for e-maintenance related to maintenance support and tools*

- *Maintenance documentation/record*: The e-maintenance platform has to support inventory and operation guidance (e.g. by using bar code reader, handhelds, laptops, scanners, etc.) and to provide access possibilities to external catalogues [30]. Besides, it has to collect, record, and store information regarding (a) degradation modes, (b) degradation sections of the machine, (c) degradation frequency, (d) degradation time and place, (e) time required preventing, (f) cost required to prevent, (g) suggested and/or applied maintenance practices, etc. [18]. The success of this collaborative maintenance platform depends on having a multi-tasking and multi-user operating environment, and a fast and easy-to-manage database for international experts to use to retrieve or store their aggregated knowledge and experiences [47].

### 4.3. *Needs for e-maintenance related to maintenance activities*

We can summarize these needs as follows:

- *Inspection/monitoring*: There is still a clear need for generic systems, which can offer integrated monitoring solutions by enabling information processing at different abstraction and representation levels and be customizable to diverse applications [61]. Distributed, autonomous monitoring is fundamental to the penetration of e-maintenance to the cutting edge of high capital and highly productive plants. A highly advanced sensor network should previously be presented [12], and the development of intelligent agents for continuous, real-time, remote, and distributed monitoring and analyses of devices, machinery, and systems can be necessary.
- *Modification/improvement—knowledge capitalization and management*: One of the most urgent industrial problems is how to realize knowledge-based operation and maintenance of plants [16]. The information flow collected by the e-maintenance platform has to be used for behaviour learning and rule extraction purposes. Hence, a knowledge-based system can be achieved through intelligent conversion of data into information, and information into knowledge [18]. This knowledge capitalization aims at creating a corporate memory (i.e. a structured set of knowledge related to the firm experience in a field domain) of enterprise [32].

## 5. State of the start in e-maintenance

As shown in Table 1, the different contributions developed in e-maintenance aim at responding to one (or more) of the four following issues: (1) providing standards, (2) designing an e-maintenance platform, (3) formalizing the e-maintenance processes, and (4) implementing an

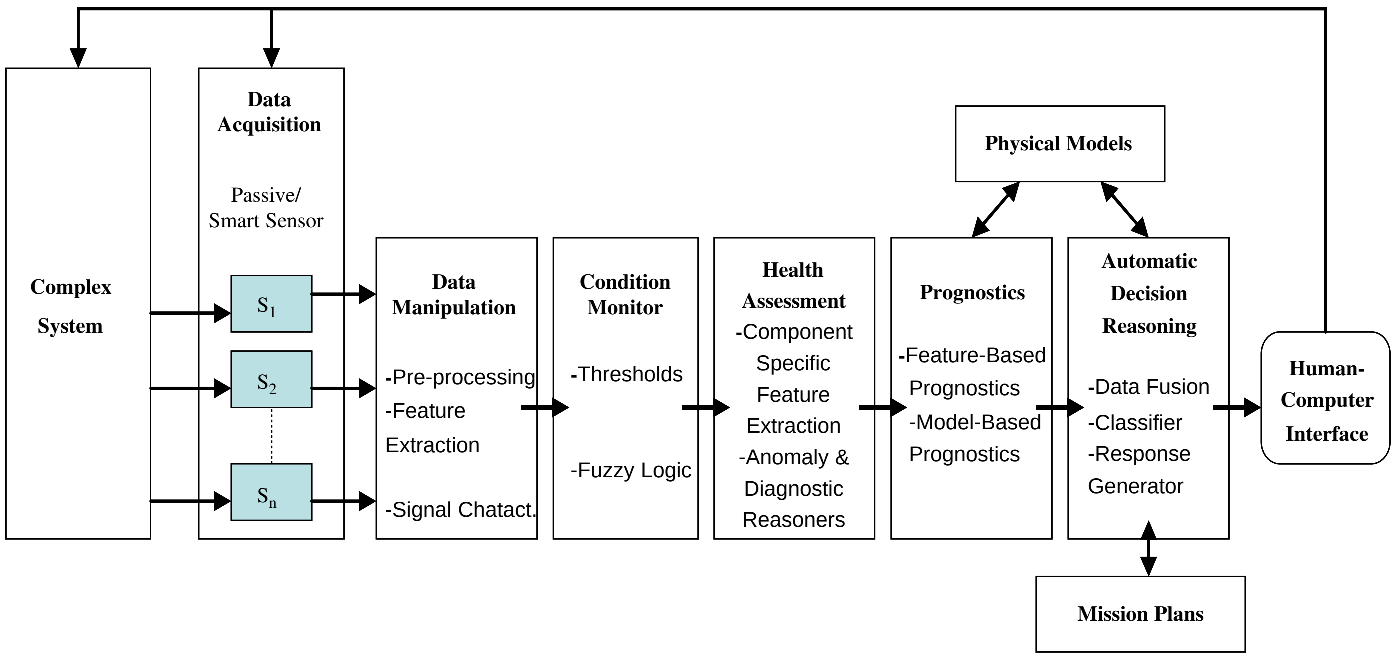



Fig. 5. OSA-CBM architecture [21].

e-maintenance system (i.e. platform + processes). In this section, we review the most interesting contributions that we have found within each one of those categories.

### 5.1. Standards development in e-maintenance

The industrial deployment of e-maintenance is supported today by different standards to help the engineers in the development of e-maintenance platforms/architectures, which are suitable for the systems to be maintained. The main existing standards are:

- IEEE 802.11x, EN457:1992-ISO7731.
- IEC 62264 (enterprise—control system integration) based on ANSI/ISA S95.
- ISO 15745 (industrial automation application integration framework).
- MIMOSA[6] (Machinery Information Management Open System Alliance)-IEEE 1232.[7]
- ISO 13374 (condition monitoring and diagnostics of machines).
- EN60204-1:1997/IEC60204-1 (safety of machinery).

Some of them have been developed within the CBM technology and are specific within CBM systems. In this area, the standardization proposals promoted by the organizations of MIMOSA and Open System Architecture for CBM (OSA/CBM) and the published standards IEEE Std. 1451, IEEE Std. 1232, and ISO 13373-1 have been examined in depth by Bengtsson [24].

Interconnectivity of the islands of maintenance and reliability information is embodied in e-maintenance. Therefore, the e-maintenance network must provide for the open exchange of equipment asset-related information between condition assessment, process control, and maintenance information systems. It can be developed from a collection of information islands in several ways: use a single proprietary system, buy a custom bridge, build a custom bridge, or use an open systems bridge [7]. The last solution seems to be the most promising. Moreover, the adoption of MIMOSA specifications can facilitate the integration of asset management information, provide a freedom to choose from a broader selection of software applications, and save money by reducing integration and software maintenance costs. MIMOSA provides a standard set of asset management data fields in its Common Relational Information Schema (CRIS) that software developers can adopt for their open systems [20]. CRIS spans all technologies, with tables for site information, measurement data, alarms, sample test data, and blob data (binary large object fields for drawings and photographs). Special maintenance and reliability tables define fields for events (actual, hypothesized, and proposed), health and estimated asset life assessment, and recommendations.

From MIMOSA CRIS and emerging standards such as the IEEE Std. 1232, an industry-led team has developed the OSA/CBM architecture. Then, they have demonstrated that OSA/CBM facilitates interoperability of CBM software modules [21]. This functional architecture has been

[6] http://www.mimosa.org/.

[7] The purpose of these standards is to provide formal models of diagnostic information to ensure unambiguous access to an understanding of the information supporting system test and diagnosis (IEEE Std. 1232-2002).

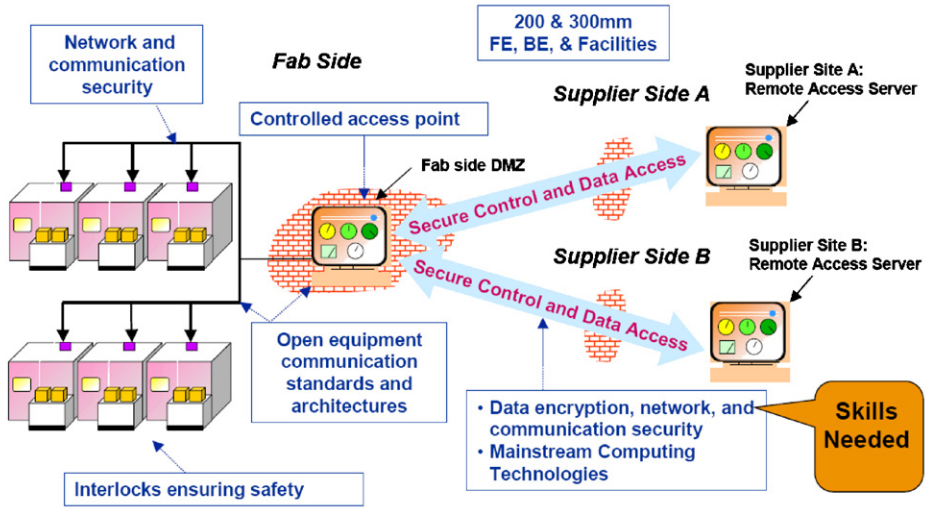



Fig. 6. Overview of the e-diagnostic guidelines [23].

described in terms of seven functional layers[8] (Fig. 5) interacting to form a complete integrated system. It incorporates the use of persistent (e.g. database) data, which are accessible from each layer, as well as persistent data support features such as trending, "black box" recording, machinery parameters (e.g., equipment nominal operating information), and equipment/process connectivity information. The OSA/CBM framework supports a variety of information models for persistent data, such as object-oriented databases, blackboard structures, or data dictionaries [22].

In addition, other future developments have to be devoted to improve the interoperability [62] of e-maintenance applications and software. As developed in the context of enterprise modelling through European initiatives such as ATHENA Integrated Project and INTEROP[9] Network of Excellence, this challenge consists in defining interoperability framework addressing three main issues:

- E-maintenance information system and business process modelling (as is … to be) based on unified languages and dealing with the representation of the interoperability requirements between all the e-maintenance applications and software.
- Architecture and platforms defining the implementation solution to achieve interoperability.
- Ontologies formalizing the semantics necessary to ensure a seamless interoperability (semantics completing the syntax of the models).

In that way, a proposed collaboration between ISO TC 184/SC5 and ISO TC108/SC5 is an interesting step by investigating ISO new work items using IEC6224 to develop reference interoperability scenarios, mapping ISO13374 into ISO 15745, using MIMOSA OSA/CBM architecture to provide a basis for describing the semantics of the information and developing ISO15745-based e-maintenance interoperability profiles.

Furthermore, the SEMATECH Company[10] has proposed e-diagnostics, e-manufacturing, and e-factory concepts to achieve electronic and unmanned factories using Internet and information technologies. It has elaborated a guidebook for selecting communication and data representation technologies to implement an e-diagnostics system for semiconductor manufacturing industry [23]. This document defines a set of guidelines, a capability and data taxonomy, security guidelines, industry use case scenarios, and an implementation roadmap (Fig. 6). The capabilities of e-diagnostics are divided into four levels[11]:

- Level 0—access: collaborative troubleshooting with basic remote connectivity.
- Level 1—collection and control: remote performance monitoring and equipment operation.
- Level 2—analysis: automated reporting and advanced analysis.
- Level 3—prediction: predictive maintenance, self-diagnostics, and automated notification.

These standards are to be looked upon with the purpose of building an e-maintenance platform or e-maintenance system. In the following section, some of the most promising platform developments are presented.

### 5.2. E-maintenance platform development

An e-maintenance platform consists of software, hardware, and new technologies allowing to offer a certain e-maintenance service. A recent literature review related to

[8] A detailed description of the inputs and outputs required for all the given layers is available through the OSA/CBM website (http://www.osacbm.org).

[9] http://www.interop-noe.org.

[10] www.sematech.org/.

[11] The capabilities in Levels 0 and 1 are considered by Hung et al. [29] as the e-diagnostics functions, while those in Levels 2 and 3 are considered as the e-maintenance functions.

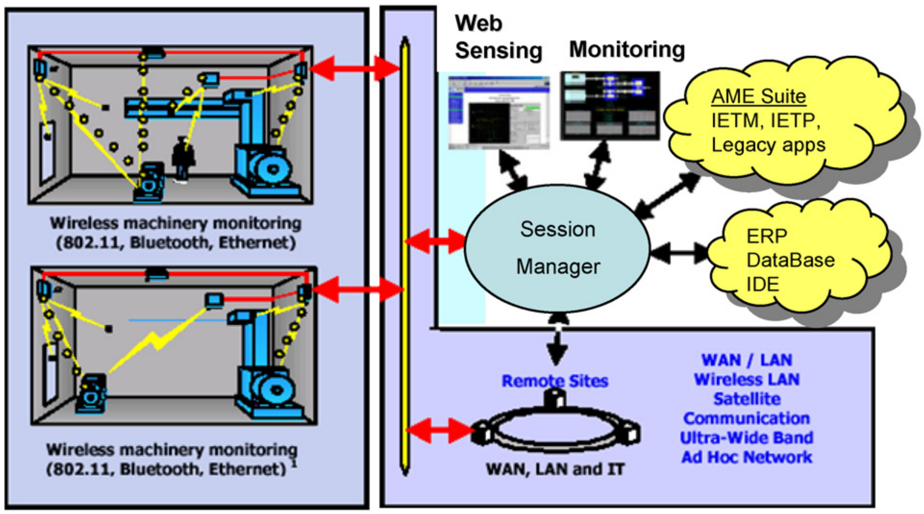



Fig. 7. Total ship monitoring implementation [26].

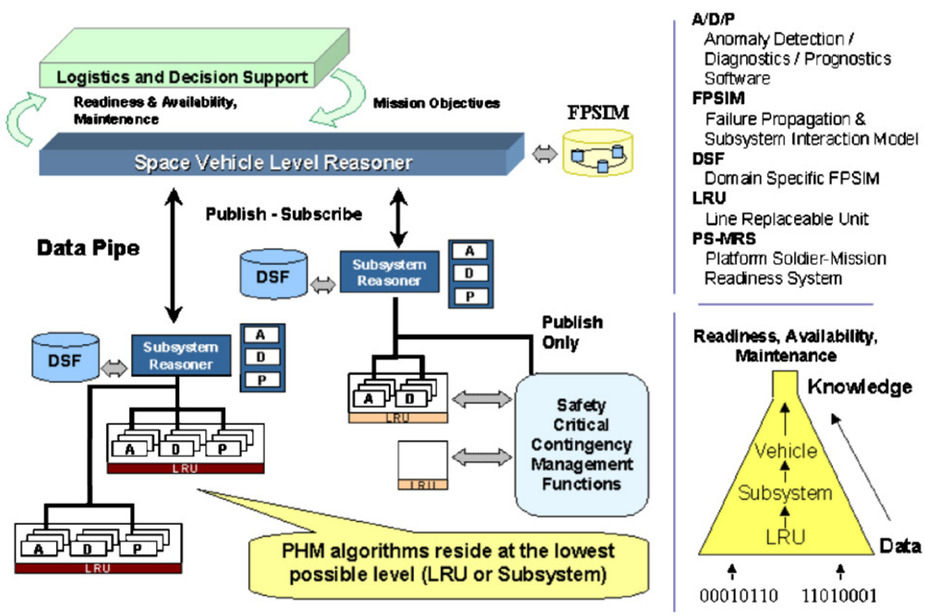



Fig. 8. Distributed Prognostic System Architecture [28].

this topic with emphasis on Web technology and multi-agent systems has been presented by Campos [25]. After having described the latest developments in the application of ICT, more specifically, Web and agent technologies, Campos et al. concluded that the current developments in these areas are still at the rudimentary stage. For Jardine et al. [41], the reasons that advanced maintenance technologies have not been well implemented in industry might be (1) lack of data due to incorrect data collecting approach, or even no data collection and/or data storage at all; (2) lack of efficient communication between theory developers and practitioners in the area of reliability and maintenance; (3) lack of efficient validation approaches; and (4) difficulty of implementation due to frequent change of design, technologies, business policies, and management executives.

However, there exist considerable incentives in developing appropriate tools, methods, or systems for solving these issues, and several e-maintenance platforms have been developed and are in use today (ENIGMA, CASIP, ICAS-AME, Remote Data Sentinel, INTERMOR, INID, IPDSS, WSDF, MRPOS, PROTEUS, TELMA, etc.). These platforms are a result either of the industrial world or of the academic one. They can be classified[12] as proprietary platforms (i.e. ICAS), platforms developed within projects (i.e. PROTEUS) or platforms for research and education (i.e. TELMA). Some of these main platforms are presented below.

[12]For more details, please consult the deliverable.

### 5.2.1. Proprietary platforms

The Integrated Condition Assessment System (ICAS) is designed to provide a computerized engineering tool to implement CBM via data acquisition, historical trending, expert analysis to improve equipment availability and reliability, etc. [26]. ICAS consists of four or five workstations, one in each major machinery compartment as depicted in Fig. 7, connected by an active local area network (LAN). Each workstation accommodates a unique configuration data set (CDS), which contains the engineering information representing the equipment in that space. Besides, ICAS can be integrated to the MPROS architecture developed by a consortium led by HONEYWELL for diagnostic and prognostic of the ship machinery [27].

For next-generation NASA vehicles, Roemer et al. [28] provide an overview of a Distributed Prognosis System Architecture allowing the implementation of a prognostic and health management (PHM) system (Fig. 8). The anomaly, diagnostic, and prognostic (A/D/P) technologies implemented at the lower levels (LRUs) are used to detect and predict off-nominal conditions or damage accumulating at an accelerated rate. This information is then analysed through the hierarchy of reasoners to make informed decisions on the health of the vehicle subsystems/systems and how they affect total vehicle capability.

### 5.2.2. Project platforms

A Web-services-based e-diagnostics framework (WSDF) had been developed by the Department of Electrical Engineering, Chung Cheng Institute of Technology, Taiwan [29]. WSDF can effectively improve the remote diagnostic systems by providing the mechanism for automatically integrating diagnostics information through the Internet so that various functions required to adequately support the e-diagnostics tasks in semiconductor factories could be established. WSDF solves both security and communication problems in the e-diagnostics system (Fig. 9).

Resulting from a European ITEA project, the PROTEUS platform brings a contribution of the vertical integration of applications in the domain of remote maintenance of industrial installations [30]. It provides a unique and coherent description of the equipment (through an ontology description), a generic architecture (based on the "Web services" technology) and coherent models of heterogeneous components. The integration is based on cooperative and orchestrated execution of distributed processes run on heterogeneous hardware/software platforms and communicating via Web services. The principal objective of the PROTEUS platform is to provide the means for moving from co-existence to interoperability and cooperation of these applications within the same environment (see for example the scenario depicted in Fig. 10).

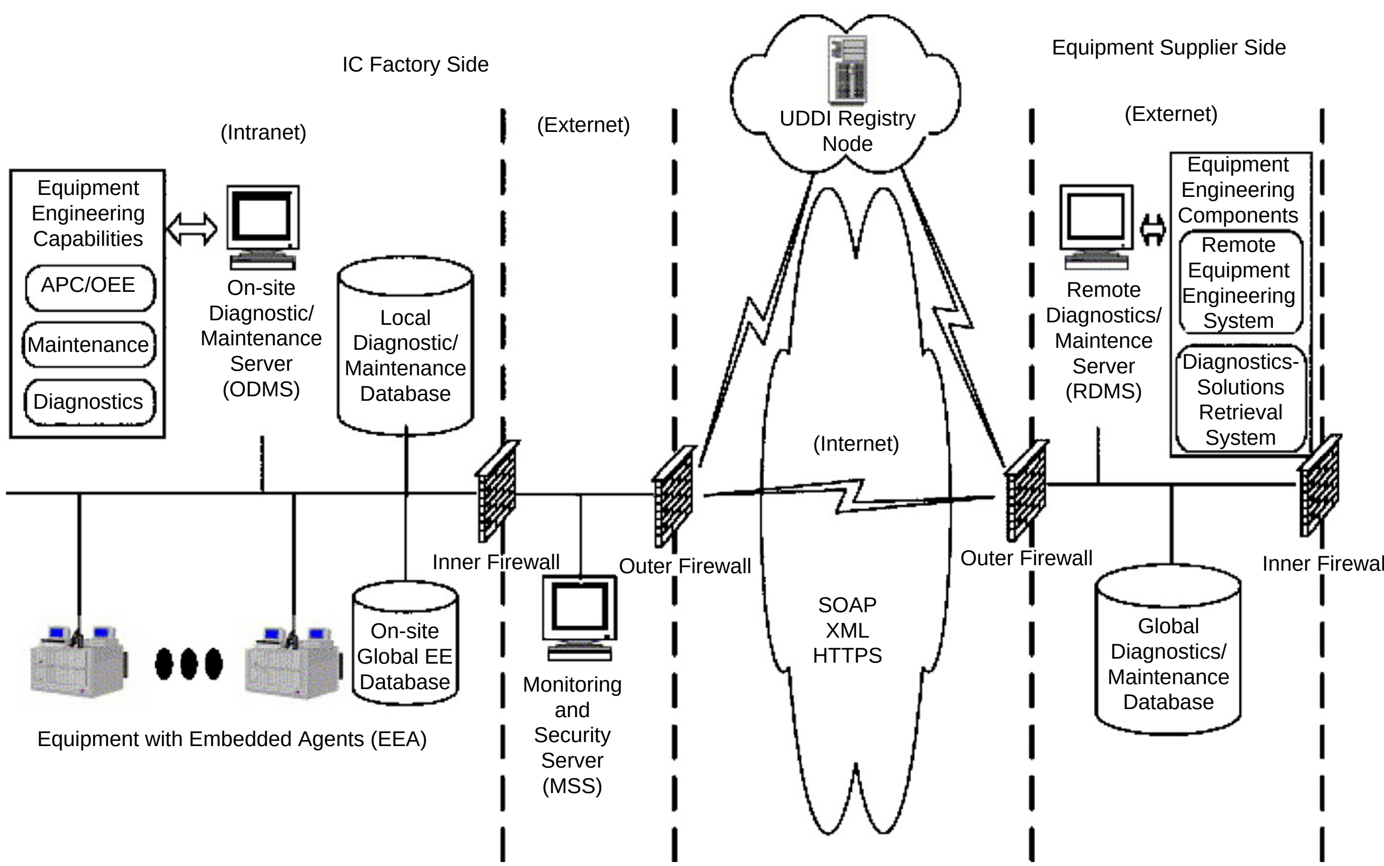



Fig. 9. WSDF with safety consideration [29].

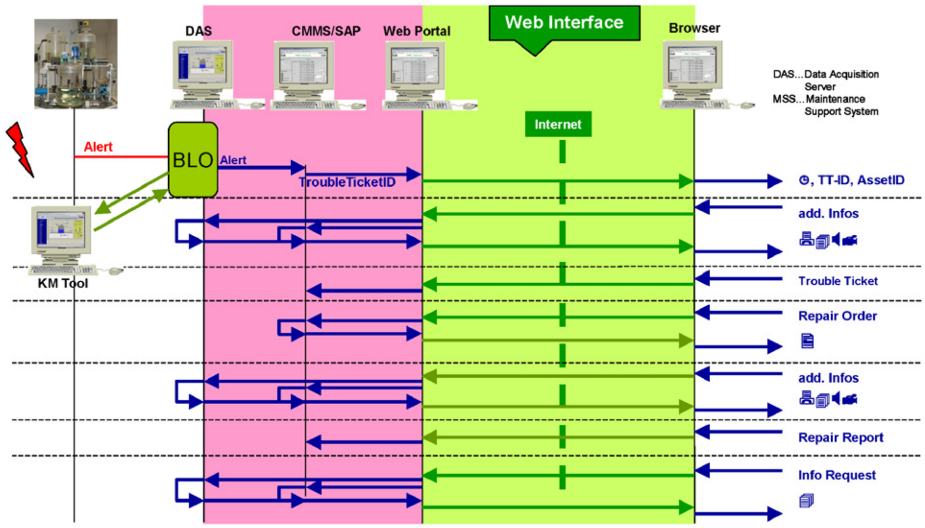



Fig. 10. Maintenance scenario supported by PROTEUS [30].

Nevertheless, the PROTEUS platform has been used as the support of several complementary studies concerning other related aspects of e-maintenance. For one, Saint-Voirin et al. [31] tried to optimize the cooperation activity. Actually, they have implemented their conceptual cooperation meta-model on the PROTEUS platform in order to simplify design operations. Their meta-model builds on the use of multi-agent systems allowed computer models and simulation of the remote maintenance cooperative system. For another, Rasovska et al. [32] tried to create a corporate memory of enterprise (i.e. a structured set of knowledge related to the firm experience) in e-maintenance. They presented a method for knowledge capitalization coupled with a decision help system for diagnosis and repair within the PROTEUS platform. The approach is based on an UML data model and on case retrieval nets (ontology), which allow one to formalize and to retrieve the knowledge. Then, a case-based reasoning tool is used for decision-making aid for operators and for the update of knowledge.

### 5.2.3. *Research and education platforms*

The first academic e-maintenance project has been developed at the Intelligent Maintenance System (IMS) centre in USA under the responsibility of Prof. J. Lee from Wisconsin University and Jun Ni from Michigan University. It supports, in the domain of e-maintenance, the deployment and experimentation of the device-to-business (D2B™) platform based on a core-enabling element: the Watchdog Agent™, which is a prognostics-based "digital doctor" [14]. The goal of the D2B™ platform is to provide transformation of raw data (or information through EIA) from device level to widely compatible Web-enabled formats (e.g. XML) so that many Web-enabled applications can be performed [33]. Once device information is available at this level, users from various part of the network users in different geographical locations can share the same information for different but synchronized applications [34]. One promising issue consists then in integrating Watchdog capabilities into product and systems for closed-looped design and lifecycle management as proposed by PROMISE[13] (consortium on product embedded information systems for service and end of life) [14].

In the long term, the objective of PROMISE is to allow information flow management to go beyond the customer, to close the PLC information loops, and to enable the seamless e-transformation of PLC information to knowledge [35]. Three working areas of the project relate to e-maintenance issues:

- *Area 1*: E-maintenance and e-service architecture design tools (design of e-maintenance architecture as well as its platform for e-service applications).
- *Area 2*: Development of watchdog computing for prognostics (development of advanced hashing algorithm for embedded product behaviour assessment and prognostics).
- *Area 3*: Web-based and tether-free monitoring systems (development of "interface technologies" between the product e-service system platform and Web-enabled e-business software tools).

In parallel of PROMISE, the new European project DYNAMITE[14] (Dynamic Decisions in Maintenance) aims at creating an infrastructure for mobile monitoring technology and create new devices, which will make major advances in capability for decision systems incorporating sensors and algorithms [36]. The key features include wireless telemetry, intelligent local history in smart tags, and on-line instrumentation.

[13] http://www.promise.no.
[14] http://osiris.sunderland.ac.uk/~cs0aad/DYNAMITE/Index.htm.

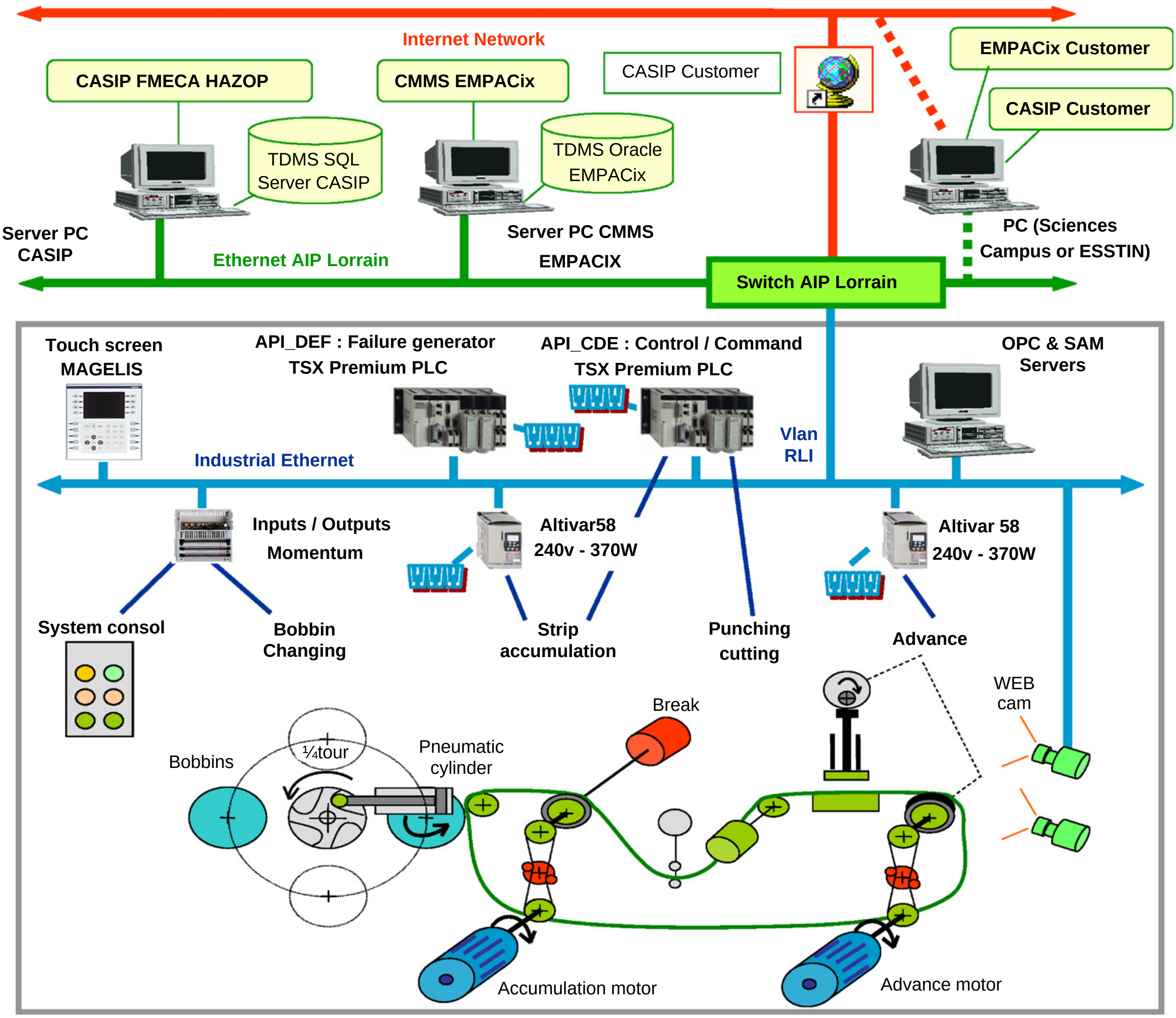



Fig. 11. TELMA platform description [9,10].

Finally, the TELMA platform[15] located at the University Henri Poincaré of Nancy (Fig. 11) has been defined to answer to a group of teachers and researchers wishing to have at their disposal a training platform in the areas of maintenance, tele-maintenance, and e-maintenance [37]. In that way, the platform is designed for (1) a local use in the frame of conventional training activities; (2) a remote use via Internet for operation on industrial e-services (i.e. tele-monitoring), and for accessing to production data, performance data; (3) a use for e-teaching and e-learning as application support of courses in the e-maintenance domains. From a research point of view, the platform is currently used to demonstrate the feasibility and the potential benefits of approaches in relation to e-maintenance (i.e. within DYNAMITE project). In particular, it supports the deployment of the prognosis process, as introduced by Muller et al. [10].

Some mechanical parts have also been added to simulate other failures and degradations. The maintenance part of the platform is built on the CASIP[16] (Computer Aided Safety and Industrial Productivity) product supporting a local real-time maintenance system, a centralized maintenance system (with Oracle) and some remote stations [38]. To this maintenance system is integrated through SQL-Server and Oracle, a lot of hardware and software components for running the maintenance actions well such as OPC server, a CMMS called EmpaciX, a Technical Data Base System called Advitium, an ERP called

[15] http://www.aip-primeca.net.

[16] http://www.predict.fr.

AdoniX, etc. Thus this e-maintenance TELMA platform has the following functionalities:

- Intelligent agents (on-line services) directly implemented at the shop-floor level into the PLCs of the components (smart systems) for continuous, real-time, remote, and distributed monitoring and diagnosis of devices to establish the device health condition [63]. These embedded agents allow transforming raw data into an intelligent and useful form for maintenance considerations (current degraded process situation). They are today a sub-concept of watch-dog agent.
- Infotronics platform supporting the data vs. information vs. knowledge processing, storing, and communication on each level (shop floor and business) but also between the two levels. It uses PLCs, field-buses, real-time data-base (local data centre), Ethernet, Oracle data-base (global data centre), CMMS, etc.
- Services (off-line) among users for aided decision-making in front of the degraded situation. These services materializes, for each expert, the assessment of the (current degraded) process performance, then the prognostics of the future situation (if the degradation is evolving) and of its expected performances, and finally the decision to be taken to control the process in its optimal performance state [69]. The assessment of the predictive process performance is developed, for example, by using MAS support, on economic, production, reliability, and availability criteria, enabling one to optimize the main CRAMP parameters by keeping of course a priority on safety [39].

### 5.3. E-maintenance processes formalization

A global e-maintenance system integrates a set of shop-floor processes (prognosis, diagnosis, monitoring, etc.) to better master the manufacturing system degradation as well as a set of enterprise processes (cost, management, policy, etc.) to better master the capability of the whole enterprise system [60]. The literature on design, development, and integration of theses processes[17] is huge, including theories and practical applications. As this paper does not aim at giving a deepening in this area, the reader is referred to the two recent reviews papers proposed by Venkatasubramanian [40], Jardine et al. [33], and Ali et al. [41].

In the first one, Venkatasubramanian gives a broad overview of the various approaches to automated fault diagnosis and describes the state-of-the-art efforts in terms of industrial applications in the field. He also presents the relevance of automated process hazards analysis to abnormal events management in PLC management. In the second one, Jardine et al. summarize recent research and development in machinery diagnostics and prognostics of mechanical systems implementing CBM. Various techniques, models, and algorithms have been reviewed following the three main steps of a CBM programme, namely data acquisition, data processing, and maintenance decision-making, with emphasis on the last two steps. Different techniques for multiple sensor data fusion have also been discussed.

In a complementary way, the PROTEUS WP2 Team presents an overview of the integration of artificial intelligence tools (rule-based systems, case-based reasoning, self-organizing maps, neuro-fuzzy systems, hidden Markov models) in the platform to perform diagnosis or prognosis [42]. They define firstly a generic AI template for specifying how AI tools must be integrated into the platform and then, specify the features of a meta-tool that, for a given diagnosis or prognosis task, would help decide which tools are best suited. Besides, Roemer et al. [28] present a variety of techniques applied to fault prognosis ranging from Bayesian estimation and other probabilistic/statistical methods to artificial intelligence tools and methodologies based on notions from the computational intelligence arena. Depending on the criticality of the system being monitored, various levels of data, models, and historical information will be needed to develop and implement the desired prognostic approach (Fig. 12).

### 5.4. E-maintenance system implementation

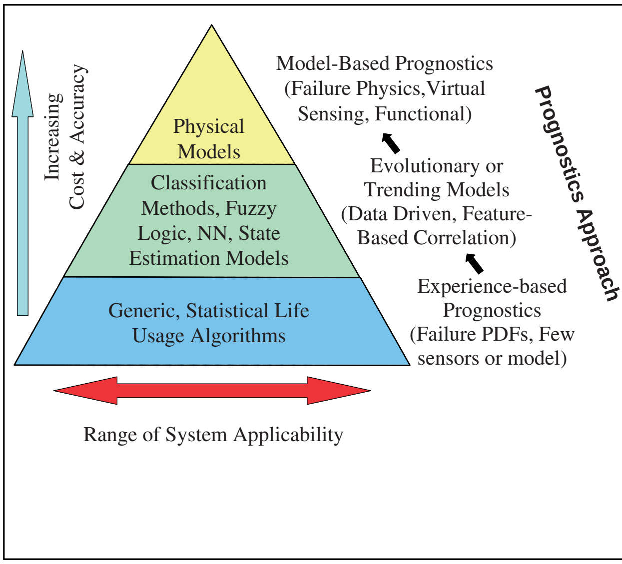
In the next paragraphs, we review and summarize several initiatives (up to 10—see Table 1) pursuing a certain e-maintenance system development and implementation.

This is the case of Han et al. [11]; they work on the creation an e-maintenance system that emphasizes particularly on condition monitoring, fault diagnosis, and maintenance management through cooperation among associated areas, fusion of information resources, and integration of existent advanced techniques (e.g. feature trend analysis, AI algorithms). The system consists of two subsystems: maintenance centre and local maintenance subsystem. The former provides a sharable platform to interconnect separate experts, research centres, and manufactories based on the Internet technique. In the maintenance centre, initial industry maintenance CBR system and condition monitoring and fault diagnosis systems are completed.

Garcia et al. [43] propose a hardware and software solution, allowing making a cooperative tele-maintenance: the maintenance staff may not only do their work remotely (tele-maintenance), but can also do it in collaboration with other experts (cooperative work). The key point of their TEMIC platform is the implementation of a new neural network architecture called RRBF (Recurrent Radial Basis Function) for breakdown prediction and diagnosis bring a suitable answer to data complexity in tele-maintenance and a good reactivity for real-time systems.

[17] Especially (e-)condition monitoring, (e-)diagnostic, and (e-)prognostic.

a




b

Pronostic Accuracy →

| | Experienced based | Evolutionary | Physics based |
|---|---|---|---|
| Engineering Model | Not required | **Beneficial** | **Required** |
| Failure History | **Required** | Not required | **Beneficial** |
| Past Operating Conditions | **Beneficial** | Not required | **Required** |
| Current Conditions | **Beneficial** | **Required** | **Required** |
| Identified Fault patterns | Not required | **Required** | **Required** |
| Maintenance History | **Beneficial** | Not required | **Beneficial** |
| **IN GENERAL** | No sensors/ No Model | Sensors/ No Model | Sensors And Model |

Fig. 12. An overview of prognosis technical approaches [28]. (a) Hierarchy of prognostic approaches. (b) Information necessary to implement the approaches.

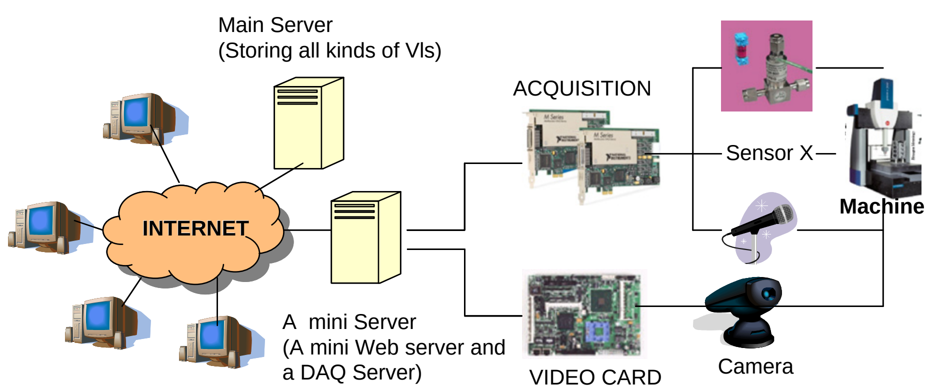



Fig. 13. The layout of the Web-based maintenance [47].

While most existing approaches are not well adapted to manage modern equipment, Bae et al. [44] describe a real-time intelligent multiple fault diagnostic system (RIMFDS) designed for complex systems such as airplanes, spaceships, nuclear power plants, etc. This system deals with multiple fault diagnosis, and is based on multiprocessing by using a strata hierarchical artificial neural network. It can simultaneously diagnose multiple faults according to information on machine conditions from dozens of sensors. The RIMFDS modules[18] include a neural network model for diagnosis, a simple numerical model (e.g., crack growth, fatigue model) for predicting the health condition of a machine component, and a communication module for synchronizing processes and cooperation between models.

Yam et al. [45] introduce an intelligent predictive decision support system[19] (IPDSS) based on a recurrent neural network (RNN) model. This integrated system aims at supplementing the conventional CBM approaches by adding the capability of intelligent condition-based fault diagnosis and the power of predicting the trend of equipment deterioration for maintenance management.

Goncharenko and Kimura [46] proposed an information-centred approach to remote maintenance based on criteria of PLC optimization and inverse manufacturing (IM) philosophy. They described the input parameters for modelling and methods for their quantitative estimation. Then, they focused on criteria for decision-making in order to generate optimal maintenance actions. Finally,

[18]A module consists of models and agents that can process expert knowledge. These modules and agents communicate and cooperate with each other across a blackboard conceptual area.

[19]A decision support system (DSS) is a computerized information system, which contains domain-specific knowledge and analytical decision models to assist the decision maker by presenting information and the interpretation of various alternatives [45].

a supporting information infrastructure system (IIS) for remote maintenance activity is discussed. The four general functions of this IIS are (1) multi-sensor integrated monitoring and control; (2) communications and collaboration among remote participants; (3) data abstraction; and (4) telemaintenance and collaborative tools.

Emmanouilidis et al. [61] have developed a flexible software solution for condition monitoring, novelty identification, and machinery diagnostics, which can easily be customized to a wide range of monitoring scenarios. Its main constituents are a number of independent software modules, such as the Fault and Symptom Tree, the Fuzzy Classification module, the Novelty Detection and the Neural Network Diagnostics sub-systems.

Wang et al. [47] outline the design and implementation of a Web-based maintenance system (Fig. 13), which consists of a remote sensing and multi-media-based monitoring system, local mini-servers, each of which is embedded with a mini-Web server and a data acquisition server, a main server for storing a number of Web-enabled virtual instruments for equipment fault diagnosis, and a collaborative maintenance platform suitable for a multi-user working environment.

García et al. [48] propose a predictive maintenance system, called SIMAP, based on artificial intelligent techniques (Fig. 14). This system takes into account the information coming in real time from different sensors and other information sources and tries to detect possible anomalies in the normal behaviour expected of the industrial components. The incipient detection of anomalies allows for an early diagnosis and the possibility to plan effective maintenance actions. SIMAP implements a neural network model for the fault detection, a fuzzy expert system for diagnosis, a neural network model for failure time forecasting, and a fuzzy genetic algorithm for the scheduling of maintenance task.

The Watchdog Agent™, an e-prognosis component, is the core of the Intelligent (predictive) Maintenance System developed by the IMS centre (Fig. 15). It consists of embedded computational prognostic algorithms and a software toolbox for predicting degradation of devices and systems. Its degradation assessment is based on the readings from multiple sensors that measure critical properties of the process, or machinery that is being considered. Degradation on system's performance can be measured using a set of tools based on a cluster of input signals from sensors and actuators from a system. A toolbox that consists of different prognostics tools has been developed for predicting the degradation or performance loss on devices, processes, and systems. The algorithms include neural network-based, time-series-based, wavelet-based and hybrid joint time–frequency methods [49].

To effectively apply this Web-enabled agent in various kinds of products and machines, its integration with working environment needs to be further developed [15].

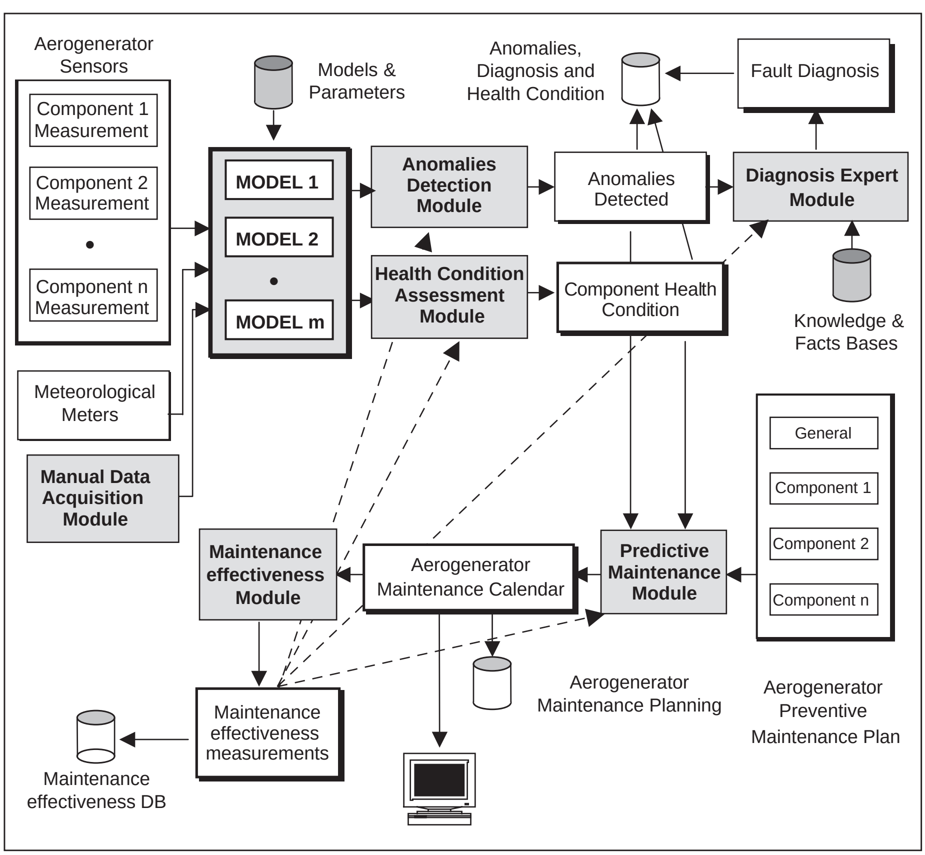


Fig. 14. SIMAP Architecture [48].

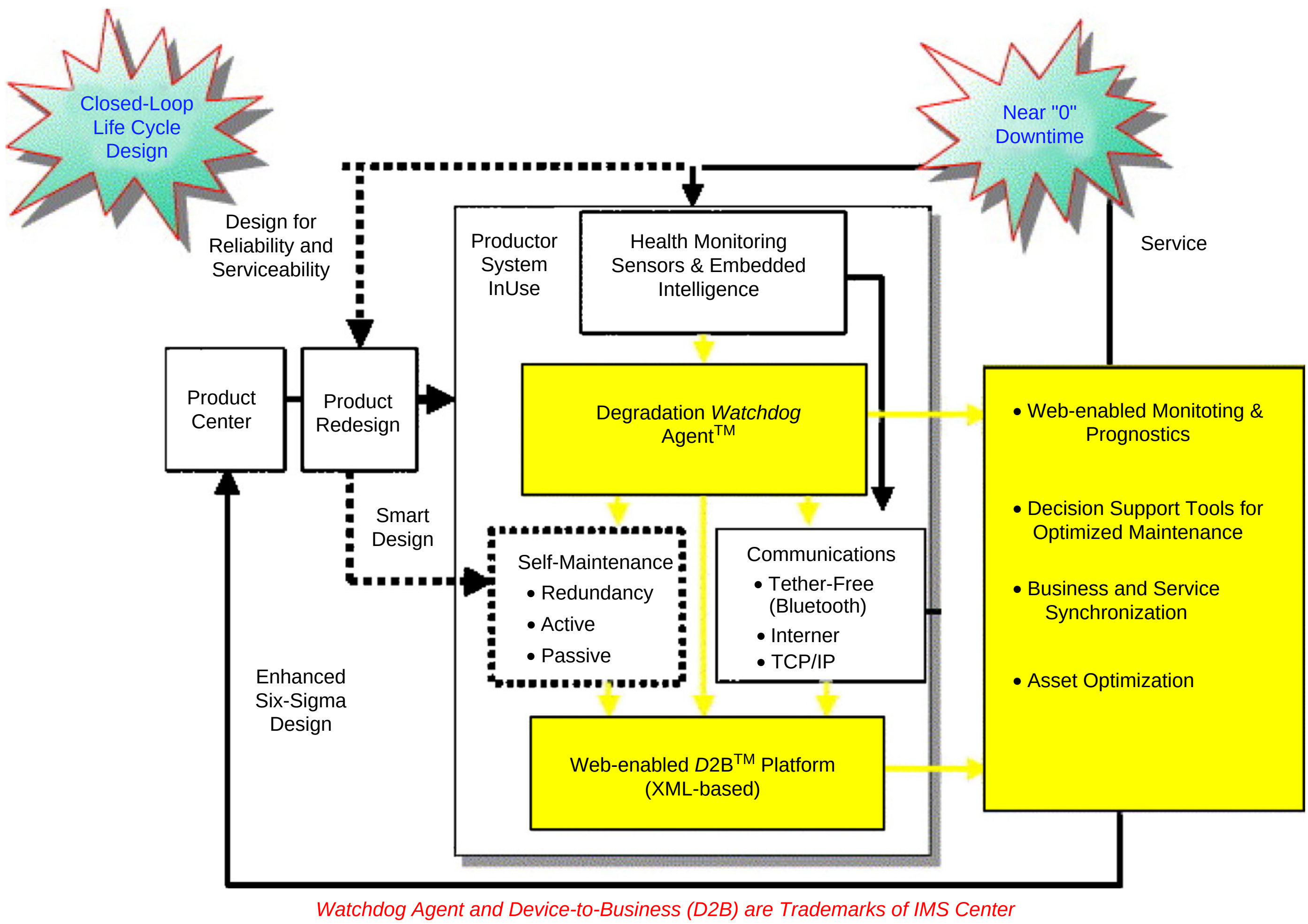



Fig. 15. Intelligent maintenance system [49].

Indeed, as the remote and real-time assessment of machine's performance requires an integration of many different technologies including sensory devices, reasoning agents, wireless communication, virtual integration, and interface platforms [34], the design and the implementation of the e-maintenance system is difficult. For example, in case of the integration of the watchdog agent with the EXAKT software within an e-maintenance platform, several interoperability problems (e.g. communication, storage, and exchange) have occurred [50]. However, in middle term, these e-maintenance systems can be harnessed through Web-enabled agents and connect them to e-business tools (such as customer relation management systems, ERP systems, and e-commerce systems) to achieve smart and effective service solutions.

Koomsap et al. [51] proposed an architecture for unifying process control and CBM scheduling within autonomous controllers in a distributed system. The objective is to select the operating parameters that consider not only the production requirement but also the constraints due to the current machine condition. Sensory information indicative of the current condition of the machine is provided to autonomous decision-making units that use the information to estimate the remaining useful lifetime of the machine. In this work, the lifetime estimator is statistically estimated using a Weibull distribution, while the maintenance scheduling is supported by a feedback control-based approach called distributed arrival time control (DATC).

Moore and Starr [52] illustrate the problems of setting simplistic condition monitoring alarm levels and introduce a method to focus attention on alarms that pose the gravest consequences to the business. This methodology, namely cost-based criticality (CBC), weighs each incident flagged by condition monitoring alarms with up-to-date cost information and risk factors, allowing an optimized prioritization of maintenance activities. The strategy applied in a food manufacturing uses a thin-client architecture rather than a central database.

## 6. Impact of e-maintenance to the application of existing "normal" maintenance theory

As already explained in the paper and in consistence with the definition proposed in Section 1, e-maintenance has to be considered as a maintenance "mutation". This revolutionary change takes into account innovative maintenance orientations related to lifecycle approach (i.e. maintenance-oriented lifecycle management), new services (i.e. prognosis), new capacities (i.e. pro-activity, velocity), new organizations (i.e. intelligent system), and new technologies (i.e. wireless communications). The development of these orientations is necessary based on the existing "normal" maintenance theories, concepts, models, methods, methodologies and tools, but are also required to enlarge, to impact this scientific corpus to other items (i.e. AI, ubiquitous computing, human reliability), and communities (i.e. economics, knowledge management, computer sciences) to support innovative aspect. For example, the principles (a) of man–system interaction (instead of man–machine) emerging from the collaboration between the e-maintenance actors or (b) of lean maintenance emerging from the e-maintenance finality need scientific foundations to be well used.

In that way, one objective for which we are involved is to demonstrate that e-maintenance is "scientifically and technologically" another thing that is a mosaic, a patchwork of models, technologies, standards. Thus, one mid-term academic challenge consists in structuring the e-maintenance as a new scientific discipline. A first contribution in [64] was developed in terms of an e-maintenance framework based on the Zachman framework.[20] This e-maintenance framework is structured on four abstraction levels, and for each level, models have to be built according to the different areas of interest expressed in the Zachman columns: data (what are processed?); function (how is the processing done?); people (who are involved?); network (where is the processing done?); time (when is the processing done?); motivation (objectives, constraints: why is the processing done?).

These four levels are

- E-maintenance strategic vision (business and goal), which supports the e-maintenance "scope" (in consistent with Fig. 2).
- *E-maintenance business processes*: An e-maintenance business process enables description of what an enterprise does for supporting its e-maintenance strategic vision.
- *E-maintenance organization, which supports the architect's view*: It consists in projecting the business processes (but especially the associated activities) onto one or more organizations of e-maintenance and then to assess the organizations according to the expected finalities related to the strategic and business levels.
- *E-maintenance IT infrastructure, which supports the organization's view*. This infrastructure consists of a set of specific components (hardware, software, etc.) supporting each operation required to the right implementation of the procedures (and consequently of the e-maintenance business processes and of the e-maintenance strategic vision). It materializes the information technology means required (ICT requirements) for running applications and for enabling communication between these applications according to their distribution on site.

[20] http://www.zifa.com.

A set of these models (theoretical, applied, etc.) is already existing because it has been issued from maintenance [65] and now e-maintenance work as shown by the inventory done in this paper (i.e. references of Jardine, Lee, Matthew, Crespo-Marquez, Byington, Luo, Parida, Al-Najjar, etc.). But as the whole of these models does not yet cover all the "boxes" of the e-maintenance framework, future contributions are required to lead to a global e-maintenance formalization knowing that it is a hard challenge from an exhaustive point of view. These new models materialize the main impact of e-maintenance to the application of existing normal maintenance theory.

## 7. Conclusions

This paper presents an overview of the current research and challenges in e-maintenance. We have firstly offered a definition for the e-maintenance concept, that, aligned with the recent European standards for maintenance terminology, considers e-maintenance as a maintenance support. Then, the main factors allowing this new maintenance support to arise have been presented. The e-maintenance capabilities and the current challenges in this area have also been summarized. At last, a state of the art showing current research of both industrial and academic communities has been proposed.

According to our findings, e-maintenance is more than the implementation of a maintenance strategy, a maintenance plan, or a maintenance type. It supposes a maintenance revolutionary change rather than a maintenance evolutionary advance [66]. As e-business few years ago [67], the impact of e-maintenance is probably overestimated in the short run, but underestimated in the long run.

Among the future common industrial/academic working/research directions, several can be underlined:

- Incorporation and adaptation of new technologies concerning "intelligence devices" (PDA, smart tags, etc.).
- Industrial adoption and integration of the relevant standards (e.g. interoperability requirements).
- Modelling and implementation of the new processes (e-monitoring, e-prognosis, e-logistics, etc.).
- Need of theory and tools for mastering the behaviour of the interactions of the system–maintenance–economy model, and maintenance decision support system for cost-effective decisions.
- Development of new infotronics-based e-maintenance systems integrating new protocols for collaboration and negotiation, maintenance workflow, maintenance Web services, etc.

The following academic challenge will consist in structuring this e-maintenance knowledge in order to define a new framework and more precisely a new scientific discipline devoted to "e-maintenance".

## 8. E-maintenance terminology

### 8.1. Vocabulary related to e-maintenance

[7]: e-maintenance infrastructure, e-maintenance network
[5]: e-maintenance initiatives (e-CBM, e-CMMS), e-maintenance model (information architecture)
[11]: e-maintenance system
[30]: e-maintenance solutions, e-maintenance platform
[31]: e-maintenance member
[29]: e-maintenance framework
[58]: e-connection
[6]: e-maintenance logistics
[15]: e-operations, e-diagnostics, e-prognostics, e-maintenance enterprise system
[8]: e-monitoring, e-maintenance scheme
[47]: Web-based maintenance
[36]: IT-based maintenance
[32]: semantic e-maintenance system (S-maintenance).

### 8.2. Closed concepts

- *Collaborative maintenance*: A collaborative maintenance strategy can manifest itself in a wide variety of ways, such as on-line condition-based or real-time manufacturing process control monitoring, direct access to technical assistance, organization or procedural changes, customized employee training, storeroom management, onsite support, or enterprise asset-management integration tools. Collaborative maintenance is not a technology or a software solution; rather, it is a customized business strategy unique to each situation [68].
- *Remote maintenance*: Remote maintenance is considered as a distributed process incorporating remote product monitoring, computerized decision-making, and on-line maintenance guidance [46].
- *E-manufacturing*: E-manufacturing is a transformation system that enables the manufacturing operations to achieve predictive near-zero-downtime performance as well as to synchronize with the business systems through the use of Web-enabled and tether-free (i.e. wireless, Web, etc.) infotronics technologies [18].
- *E-diagnostics*: The SEMATECH Company defines e-diagnostics as the capability to enable an authorized equipment supplier's field service person to access any key production or facilities equipment from outside the IC maker's facility/factory via network or modem connection [23]. Access includes ability to remotely monitor, diagnose problems or faults, and configure/control the equipment to bring it into full productive state rapidly and within security, safety, and configuration management guidelines.
- *E-decision-making (or decision support)*: This process integrates information necessary to support a "decision to act" based on data and information from other processing blocks and external constraints (safety, environmental, operational goals, financial incentives, etc.), provides prioritized notifications with recommended maintenance and/or operational changes [21].
- *Information-based maintenance*: The overall concept of information-based maintenance is that of updating decisions for inspection, repair, and maintenance scheduling based on evolving knowledge of operation history and anticipated usage of the machinery, as well as the physics and dynamics of material degradation in critical components.
- *Semantic e-maintenance (S-maintenance)*: Collaborative e-maintenance is based on the notion of semantics. Systems in the network share the semantics created for the common architecture of e-maintenance platform. The creation of domain ontology like using knowledge and competencies in the network leads to the development of corporate memory of enterprise. This memory supports the techniques of knowledge management and permits one to capitalize on this acquired knowledge [32].

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