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Erkki Jantunen
Unai Gorostegui
Urko Zurutuza
Michele Albano*
Luis Lino Ferreira*
Csaba Heged_1s
Jaime Campos

*CISTER Research Centre

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*CISTER Research Centre

Polytechnic Institute of Porto (ISEP-IPP)

Rua Dr. António Bernardino de Almeida, 431

4200-072 Porto

Portugal

Tel.: +351.22.8340509, Fax: +351.22.8321159

E-mail: mialb@isep.ipp.pt, llf@isep.ipp.pt, jaime.campos@lnu.se

http://www.cister.isep.ipp.pt

Abstract

This article discusses how a business model based on traditional maintenance can evolve to generate servitization strategies, with the help of remote maintenance support. The application of cyber-physical systems and cloud technologies play a key role for such maintenance purposes. In fact, the utilization of large quantities of data collected on machines and their processing by means of advanced techniques such as machine learning enable novel techniques for condition-based maintenance. New sensor solutions that could be used in maintenance and interaction with cyber-physical systems are also presented. Here, data models are an important part of these techniques because of the huge amounts of data that are produced and should be processed. These data models have been used in a real case, supported by the Machinery Information Management Open System Alliance Open System Architecture for Condition-Based Maintenance standard architecture, for streamlining the modeling of collected data. In this context, an industrial use case is described, to enlighten the application of the presented concepts in a working pilot. Finally, current and future directions for application of cyber-physical systems and cloud technologies to maintenance are discussed.

Remote Maintenance Support with the Aid of Cyber-Physical Systems and Cloud Technology

Erkki Jantunen
VTT Technical Research Centre of Finland Ltd
Espoo, Finland

Unai Gorostegui,
Urko Zurutuza
Mondragon University,
Mondragon, Spain

Michele Albano,
Luis Lino Ferreira,
CISTER, ISEP/INESC-TEC
Polytechnic Institute of Porto,
Portugal

Csaba Hegedűs
AITIA International Inc.
Budapest, Hungary

Jaime Campos
Linnaeus University,
Växjö, Sweden

Abstract—**This paper discusses how a business model based on traditional maintenance can evolve to generate servitization strategies, with the help of remote maintenance support. The application of Cyber-Physical Systems (CPS) and cloud technologies play a key role for such maintenance purposes. In fact, the utilization of large quantities of data collected on machines, and their processing by the means of advanced techniques such as machine learning enable novel techniques for Condition-Based Maintenance (CBM). New sensor solutions that could be used in maintenance and interaction with CPSs are also presented. Here, data models are an important part of these techniques because of the huge amounts of data that are produced and should be processed. These data models have been used in a real case, supported by the Machinery Information Management Open System Alliance (MIMOSA) Open System Architecture for Condition-Based Maintenance (OSA-CBM) standard architecture, for streamlining the modeling of collected data. In this context, an industrial use-case is described, to enlighten the application of the presented concepts in a working pilot. Finally, current and future directions for application of CPS and cloud technologies to maintenance are discussed.**

Keywords—Cyber-Physical Systems; CPS; IoT; MEMS; MIMOSA; OSA-CBM

I. Introduction

The increase in complexity and cost of current industrial equipment is becoming an important factor. It is helping to change the maintenance from a corrective to a preventive strategy and more specifically to CBM. This change is also given more emphasis by the increase in requirements related with availability, performance and quality while trying to reduce the production equipment cost during its whole life cycle. A CBM system is based on monitoring the different parameters of an asset to compare it with previously gathered data through various mathematical algorithms to do a diagnosis on the health level of the equipment and predict how it will behave in future.

This way, the downtimes of the machines can be scheduled, so that they affect least the production, decreasing the unpredicted standstills and increasing the availability, and consequently the Overall Equipment Effectiveness (OEE). The ultimate goal of a CBM system is to link it with the Computerized Maintenance Management System (CMMS), which is a software package that maintains a computer database containing an organization's maintenance-related data. A CMMS is partially used to schedule maintenance operations in a factory, and supports decisions taking regarding maintenance operation in the broadest sense (e.g. comparing the cost of early preventive maintenance vs unexpected machine breakdowns). Thus, CBM takes part in the maintenance process by creating action reports for the technicians, shutting down a machine or reducing the speed if the system, if predicts it necessary.

The Information and Communication Technologies (ICTs) move at a rapid pace in all domains/areas and have become an integrated part of those processes and activities where they are utilized. This is also the case in industrial maintenance where the ICTs have been used in many forms to support their processes [1]. The Internet and its web technology popularity have headed several emergent technologies such as the e-maintenance, the cloud computing, the Internet of Things (IoT) and the Industry 4.0 concepts [2]. Subsequently, the drives of the new Industry 4.0 objective is to connect these new emergent ICTs to generate smarter factories resulting on the revitalization of the manufacturing sector as well as encouraging a new industrial revolution. Consequently, there are currently two inevitable trends and challenges in manufacturing industries: i) the CPS-based manufacturing and ii) Service innovations, such as cloud computing [2]. The capabilities of cloud-based systems are usually exposed using Service Oriented Technologies (SOA) [3] or using specific kinds of middleware [4]. The security aspects are rather important when the cloud computing is used. The security strategies that have been developed since the 80's, however they are not applicable to cloud computing. The prime reason for this increased importance of security is that the servers', which are part of the cloud are not in the same domain, i.e. the data owner and cloud computing servers are normally in two different domains. Consequently, numerous efforts have been made considering this matter, system models and security strategies are being debated and tried, explicit for cloud computing systems [5].

Some existent works on Cyber-Physical Production Systems (CPPS) and future aspects of maintenance reinforce its importance [6-9]. In [6] the authors mention that cyber-physical systems (CPS) are one of the most significant advances in the development of computer science, information and communication technologies which are crucial for the achievement of the industry 4.0 and the so-called 4th industrial revolution. This work reviews the literature in the filed with the aim to understand the impact of the CPS and their relation with the manufacturing domain. In addition, it aims to apprehend how the CPS has advanced in the area, i.e. in connection with different applications and techniques in the maintenance sphere. The authors conclude that the manufacturing science and technology research activities of the past decades have paved the way for a relatively smooth entry into the CPS era. The area of CPPS is considered crucial for the achievement of future manufacturing systems. It is, however, important to underline the significance of further research in the area to be able to reach the Industry 4.0 goals. Further, in [7] the authors investigate service innovation based on digitalization and CPSs as well as their impact on the service ecosystem on the industrial field and their matching business models. While, in [8] they propose a systematic approach to implement the CPSs to predictive production systems. In addition, the authors propose a framework as well as deep learning-enhanced prediction approach for companies using the predictive production systems. The work in [9] highlights the importance of the CPSs systems and the potential impact they might have as a force to move industry into the 4th Industrial revolution, i.e. industry 4.0.

In conclusion, the use of the CPSs and other emergent technologies results in new business models as well as services that will change many aspects of how industry currently operates. In addition, it results in new processes that have control of the whole value chain. Thus, the technological developments provide a path/entrance into the future manufacturing systems with all what it entail. At the same time is requires new business models to be implemented.

All the technologies presented in the current paper such as sensors and clouds as well as OSA-CBM modules are intended to be part of a future maintenance multiple tier architecture that considers such technologies as CPSs and the clouds, which are the pillars of the industry 4.0. Therefore, these technologies can be conceptually visualized as part of an OSA-CBM architecture that considers the sensors, CPSs as well as the cloud storage as part of the data acquisition layer, i.e. an OSA-CBM architecture that considers the emergent aspects of the industry 4.0.

Further, the emergence of new technologies such as Micro Electro-Mechanical Systems (MEMS) sensors and their constant price drops have enabled maintenance strategies such as CBM to become more and more popular, at a lower cost, and achievable during the last few years. Moreover, the shift of paradigm towards the IoT is allowing the communication between machines and enterprise components that take part in an industrial plant. In here, connected with the cloud technologies, it is now permitted for users to obtain the data of CPSs from anywhere and on a wide range of devices.

The focus of this paper is to reinforce the idea that a maintenance system supported by CPS and cloud technologies can be beneficial in the increasing of the OEE and reducing the maintenance costs. In section II, the CBM principles are described, followed by a description of new sensors technologies that have made their entrance to CBM domain by means of their flexibility and low cost, in section III. Section IV emphasizes the cloud computing basics and its application to CBM. Section V explains the data models used in CBM, particularly focusing on MIMOSA and OSA-CBM solutions. A use case is presented in Section VI, which highlights how these technologies are integrated into an industrial pilot of the MANTIS project. In order to push this solution into the market a business model has to be developed, which fulfills the requirements of the machine manufacturers and its clients - Section VII. Finally, in Section VIII some conclusions are drawn.

II. Condition-Based Maintenance

Modern technologies applied to maintenance operations can allow for the raising of e-maintenance [10]. There exists a number of definitions for this term see e.g. Karim's doctoral thesis [11]. However, the simplest one is to define e-maintenance as a technology that supports maintenance by means of information collected by IoT devices. Consequently, e-maintenance can be seen as a sub-category of IoT concentrated on the support maintenance activities, and in particular CBM.

With respect to a traditional remote maintenance scenario, the main objective of a CBM system is not only to monitor an asset, but also to take direct action (decisions) in its maintenance, by means of leveraging multiple data sources and advanced data analysis to distil all collected data into high-level information leading to informed decisions. To fulfil this requirement, the CBM system can make use of CPSs, since they can integrate the physical monitoring of the equipment with computer-based algorithms connected to the internet and its (remote) users. Furthermore, CPS would fit into this framework as the technology where the hardware and software form an intelligent solution that can perform tasks that are needed to carry out efficient CBM under the e-maintenance umbrella.

Additionally, in most of the systems being maintained there are already many sensors, usually used for automation purposes, whose information can also be used for CBM operations. The systems at hand provide the infrastructure to create CPPSs, as long as collected data are distilled into information, to enable informed and intelligent actions to be performed in order to improve the production process. For example, in this way a CPPS is able to leverage the information to automate, or at least support, maintenance actions, implementing self-maintenance and self-repair strategies. Together with cloud-based processing, machine behaviors can be compared with information bases on potential breakdowns, leading to early diagnostics and prognostics of machine failures.

CPSs in this case can consist of various components. For example, a transducer or sensor that would measure a meaningful parameter of the asset to be monitored, can be linked to a data acquisition equipment, where the gathered signals are processed using mathematical algorithms. Once the proper information is acquired, a diagnosis can be made to evaluate the health level of an asset at that point in time.

This diagnosis is then based both on mathematical models of the system (e.g. statistical models or machine-learning) and on the assessment of the historically gathered data stored in a database. In here, the system should be able to predict the future health states and the possible failure modes based on the current health assessment.

It is worth mentioning that some companies are already offering solutions, as a software platform, that implement the data analysis and pattern recognition algorithms to help the integration of a CBM strategy with their system [12, 13]. Typically, these commercial solutions are able to carry out diagnosis of the condition of a certain set of components and fault types associated with them. However, there is no prognosis element that would predict the future development of these faults yet.

Based on the diagnostics and prognostics information, the CBM system could take pertinent actions to optimize the remaining lifetime of the asset. These actions could vary depending on the outcome of the system, from shutting down an engine, to creating an action report with the instructions to change a component and send it to the maintenance technician that is available (or closest) at that moment. This can be well understood in the following simple scenario.

If we consider a filter that is starting to get clogged, it can cause an increase in the power consumption of the motor and can increase the operating temperature. Therefore, if the motor were to keep working at this level, soon the temperature would get to a point that is not permitted or could cause a breakdown. The system realizes this trend (fault detection and root cause analysis) and sends the maintenance technician a report stating that the filter needed to be changed, while also giving the location of the machine, additionally, it reserved the tools needed for the repair and a spare parts list. Then it schedules the maintenance operation outside the working hours.

Today, it is possible to build a system that fully automatically carries out the above described tasks. In the Dynamic Decisions in Maintenance project [10], all the necessary elements were covered. Even though technically possible and nowadays at reasonable cost, such automatic solutions is only used for very basic fault types for very cheap spare parts. For more sophisticated machines, humans are always involved in the process. Moreover, the number of solutions where the expected lifetime of components is predicted with reasonable accuracy is still rather limited. Currently, the MANTIS project [14] aims to cover these gaps and provide a fully working CBM system.

III. New sensor choices

New developments in sensing has created low-cost devices capable of acquiring signals of reasonable quality from the environment. The quality of the data is in fact sufficient to detect and monitor state changes in the operations of machinery, while at the same time enabling for a new paradigm that encloses the deployment of sensors in places and in quantity that was not possible before in a realistic industrial, business scenario.

Important members of this new family of sensor technologies are MEMS sensors. The name already reveals that MEMS are components that combine microelectronics and micromechanical parts together in the same package. MEMS sensors are manufactured using the same methods as Integrated Circuits (IC) and thus the price of an individual sensor is relatively low [15] and its size can be extremely reduced, fitting for retrofit mounting for CBM.

With different MEMS sensors it is possible to measure a lot of different phenomena from the physical environment, including temperature, acceleration, pressure, inertial forces, chemical species, magnetic fields, radiation, etc. [15]. However, it should be noted (as always) that while choosing a sensor, great care must be taken so that the sensor is suitable for the monitoring purpose. The parameters and capabilities (e.g. sampling frequency) of the sensors shall be sufficient to detect the early indications of faults, which quite often are hidden under other influencing factors.

As an example, current MEMS accelerometers of the lowest price might have bandwidth, resonance frequency and environment-resistance issues [16]. On the other hand, the piezofilm accelerometer [17] is much more expensive, but it is light, bendable, durable and easy to form for specific measuring locations [18]. Even though characteristic values of these (e.g. [19]) look very promising on paper, the experience with piezofilm sensors is still limited when compared to the long history with piezoelectric sensors.

Another example is vibration monitoring which is especially suitable for monitoring the wear of the components in rotating machinery. It is possible to detect various fault types, e.g. unbalance (seen at rotational speed), misalignment (seen at the harmonics of the rotational speed), bearing faults (seen at the so-called bearing frequencies), or gear faults (seen at the gear tooth frequencies). MEMS accelerometers suffer from lower bandwidth, lower resonance frequency, poorer “off-the-shelf” protection against harsh and difficult measuring environment and higher noise, particularly when compared against piezoelectric accelerometers.

Leveraging data made available by sensors depends on the collection of data from the MEMS, and sensor in general, up to where the data can be processed for the sake of maintenance purposes. This goal is served by a two-step transportation of the data. First, the sensors are included into a CPS that provides data preprocessing and communication to the external world. Second, a middleware must be able to transport data to the cloud. Current developments [13] studied for example how to implement this capability by means of a service-oriented architecture, which allows for connecting seamlessly different sources opening up the system to a plethora of data coming from many kinds of sensors.

To conclude, a preliminary analysis must always precede the decision regarding the type of technology to be used, where the available budget is translated into the quantity of sensors of each kind that can be acquired and deployed. Then, the potential benefits of each technology must be taken into account, for example to decide between 6 MEMS accelerometers or 2 piezofilm accelerometers to be installed over the available measurement locations, and the capabilities of the CPS the sensors are connected to. Should the scenario be susceptible to strong benefits by using a large number of measurement locations and by combining many data channels from low quality signals, the cheapest options can be chosen. The opposite can be said when the number of data channels are inherently limited by the shapes of the components to be monitored, and thus a small number of data channels can be extracted and the quality of each signal must be maximized by using a small number of better (more expensive) sensors. Finally, having opened up the CBM system to a large amount of data from a plethora of devices, data processing by means of cloud technologies is a requirement to fully process the large volumes of collected data.

IV. Clouds

The large volume of data that is collected in CBM scenarios leads to strict requirements on the computational capabilities of the platforms that enable related operations. A solution to the problem of providing sufficient computational power to data-intensive applications must also consider a number of accessory issues, starting from the confidentiality of sensible data.

Current solutions to the ever-expanding computational needs of advanced applications take the name of computational cloud [20]. The access to computational power is then provided as a service to the application stakeholders. The approach provides an elastic platform for the execution of algorithms on the data, and thus is adaptable to different volumes of data during the lifetime of distributed applications.

Usually, cloud service providers provide a web-based interface, which offers services with strong security between both the cloud and the web services. Web-based services make it possible to share the data from cloud servers to graphical user interfaces (GUI) for the end-user applications. Currently, most GUIs are supported through web browsers.

With regards to CBM, the kind of cloud to be used has to be discussed. In particular, the choice can fall either on public cloud providers, or the usage of local private clouds. There are many different public cloud service providers and among them are the big players such as Microsoft Azure, Google Cloud and Oracle. Public cloud services can be accessed with any device that has an internet connection, which can be a big advantage for the general public. On the other hand, as CBM applications are centered on a scenario where data collection, data processing and data visualization are performed in fixed locations and by a limited set of devices. It is reasonable to consider a local cloud that is deployed, tailored and managed for this specialized scenario.

The concept of local (automation related) clouds is focused on the industry. A local cloud is an intranet solution that shall provide the same computational services internally as public cloud solutions would. In here, only the devices that are inside the local network have full access to the services provided by some core, shared resources. This, in principle, is similar to the large commercial cloud systems, except on its computational elasticity. In some cases, the local clouds can be accessed also by outsiders, for trusted parties, in a restricted and controlled manner.

From an e-maintenance and CBM point of view, this access to data within local automation networks is an essential aspect. For example, a machine tool manufacturer would like to provide maintenance services for the machine tools they have sold. In order to carry out maintenance in an efficient way they would like to use a CBM strategy and thus instrument the machine tools with CPS, which in turn means that they need access to the data from the machine tools, which as such can be considered as local clouds within the local clouds the end user has at their plant.

A number of collateral issues are related to local cloud, such as the ownership of the data and security, and solutions to these issues are not yet mature for many environments. A great deal of discussions on these issues can be for example found in [19], which presents the results of a recent European project called Arrowhead in terms of theoretical findings and developed solutions, as well as open software that can be used as basis in order to provide a solution to some of the above-named challenges.

V. Data Management for CBM

In most cases, multiple stakeholders must interact to implement CBM, leading to the importance of interoperability in these scenarios. The access to the cloud platform and to its data must then be mediated by standardized protocols, and data must be modeled by means of ontologies accepted by the industry.

A. Data Communication

The interaction between the GUI of the end users and the cloud are usually based on web technologies. Web-based services integrate easily with web applications created using server-side scripts (Microsoft ASP.NET, Hypertext Preprocessor (PHP), etc.) and client-side scripts (JavaScript (JS), Hypertext Markup Language (HTML), Adobe Flash, etc.).

There are Web services that are made more for industries like Open Platform Communications Unified Architecture (OPC UA). OPC UA is an industrial Machine to Machine (M2M) communication protocol. It consists of an OPC client that interacts with an OPC server. OPC UA increases interoperability and is designed to be able to have soft real-time data access, historical data for analytics. It also supports the reporting of data or events. Alarms and conditions are used to notify anomalous conditions. OPC UA offers multi-threaded operations, a multi-platform implementation (American National Standards Institute (ANSI) C programming language standard, Java computer programming language, Microsoft .NET Framework), standard based security and safety, among others. High level of security in OPC UA includes, among others, sequencing, use of end-to-end encryption, auditing and redundancy. The OPC foundation also provides members with Compliance Test Tools (CTTs) for test-case specifications, automated testing or interoperability workshops for tests with different vendors.

Another web service is representational state transfer (REST) which offers interoperability between computer systems on the internet. REST fully relies on the Hypertext Transfer Protocol (HTTP) standard and thus it is usable by any device that support the HTTP standard and makes it easy to connect old and new devices as the protocol keeps the same. As REST fully relies on the HTTP it is compatible with intermediate components like firewalls, proxies and gateways. It has been used on most components of the Arrowhead Framework [21], which, like OPC UA also implements services to support distributed automation.

Communication solutions based on middleware are also widespread. That is the case of the Robotic Operating System 2 (ROS2) [22], which operates over Data Distribution Service DDS [23], and message broker software RabbitMQ [4], which uses Advanced Message Queuing Protocol (AMQP) [24]. AMQP is also the solution being implemented on the latest version of OPC UA as its transport layer. The main different relies on the use of the publish subscribe paradigm, where a publishers can transparently send messages to multiples consumers, without establishing a direct connection. This characteristic contributes to the decoupling between producers and consumers and eases software development.

B. Data Meta model

A CBM system is composed of different elements, and each company might use a distinct way of connecting these elements and transmitting the information through them. To interconnect various elements in the system, the elements of the system need to speak the “same language”, hence the use of the same, standardized data Meta model. However, it can be claimed that standardization and meta-models are not the same way to ensure the interoperability in the exchanges of data during CBM processes. Indeed, three approaches can contribute to the improvement of interoperability:

- the integrated approach based on the use of standard formats
- the unified approach which requires the definition of meta-models
- the federal approach which is based on the definition of ontologies whose implementations enable the dynamical adaptation of the systems

One possible solution is based on the Machinery Information Management Open System Alliance (MIMOSA) produced Open System Architecture for Condition-Based Maintenance (OSA-CBM) [25], represented in Fig. 1, which is one of the most important open standards for information exchange between the plant and the machinery information systems. It was developed in 2001 by an industry led team, with participants from Boeing, Caterpillar and Rockwell Automation.

Even though MIMOSA is presented as a defining standard format for the data exchange, it also provides the data meta-model structure together with the definition of the ontologies of the data. In fact, one of the greatest benefits in using MIMOSA is this definition of semantics and ontologies so the party that is developing their CBM solution does not need to worry about how different types of information need to get linked together.

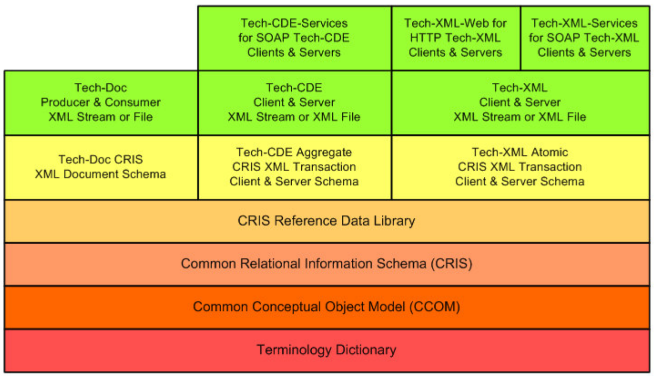


Fig. 1, MIMOSA OSA-EAI Architecture [15]

Using the OSA-CBM has multiple benefits including cost reduction, increased specialization, competition and, on the other hand, it gives also a possibility to increase cooperation. Cost reduction comes through eliminating the need of system integrators and vendors to spend time creating new or proprietary architectures and through increased competition.

It should be noted that maintenance - and especially condition monitoring - data is usually structured hierarchically, i.e. when something is measured it needs to be linked to a component of a machine that is monitored. A component needs to be linked to maintenance historical data. Condition signals need to be linked with the measured process parameters so that the condition parameters can be defined and later analyzed.

The OSA-CBM consists of multiple interoperable functional blocks as shown in Fig. 1. Therefore, the whole CBM system doesn’t have to be ordered from a single vendor but instead every block can be competed with different vendors, as provided by the Meta model architecture. The OSA-CBM follows the ISO-13374 Condition monitoring and diagnostics of machines - Data processing, communication and presentation - standard from the International Organization for Standardization. Table 1 shows the data-processing and information-flow blocks that defined in ISO-13374 and used by OSA-CBM:

Data Acquisition: The data acquisition is the first step in the different stages, as always. This is done by sensoring elements that can measure a wide range physical phenomena such as acceleration, position, temperature, pressure, etc. The signal then needs to be suited and cleaned for an accurate representation of the phenomena, so it goes through different amplification or filtering stages as well as an analog to digital conversion when necessary. Data is usually stored in a local server and then sent to the maintenance information center.

Data Manipulation: Here the signal analysis is performed, where the meaningful descriptors from the gathered signals are computed and the virtual sensor readings are created from the raw signals from the Data Acquisition block.

State Detection: It creates a “baseline state” and compares the new data to the previously created profiles to detect if there are any abnormalities, and, if so, which profile the data belong to.

Health Assessment: It diagnoses the faults and the current health level. It is usually done by analyzing the previously collected information such as health story trends, operational status or loading and maintenance history.

Prognostic Assessment: This stage determines the current health state and the Remaining Useful Life (RUL) of the monitored asset. This latter, prognostic stage can be approached in two different ways: by using a model that describes the physical phenomena of degradation or a data-driven model where a pattern recognition system is implemented alongside machine learning techniques. Both approaches have their advantages and disadvantages, but often, both methods are combined to get the best result.

Advisory Generation: It provides the information on what actions should be carried out, or takes part in the actions required to optimize the life cycle of the asset or increase the Overall Equipment Effectiveness (OEE) of the plant by decreasing the downtimes of the equipment or the process.

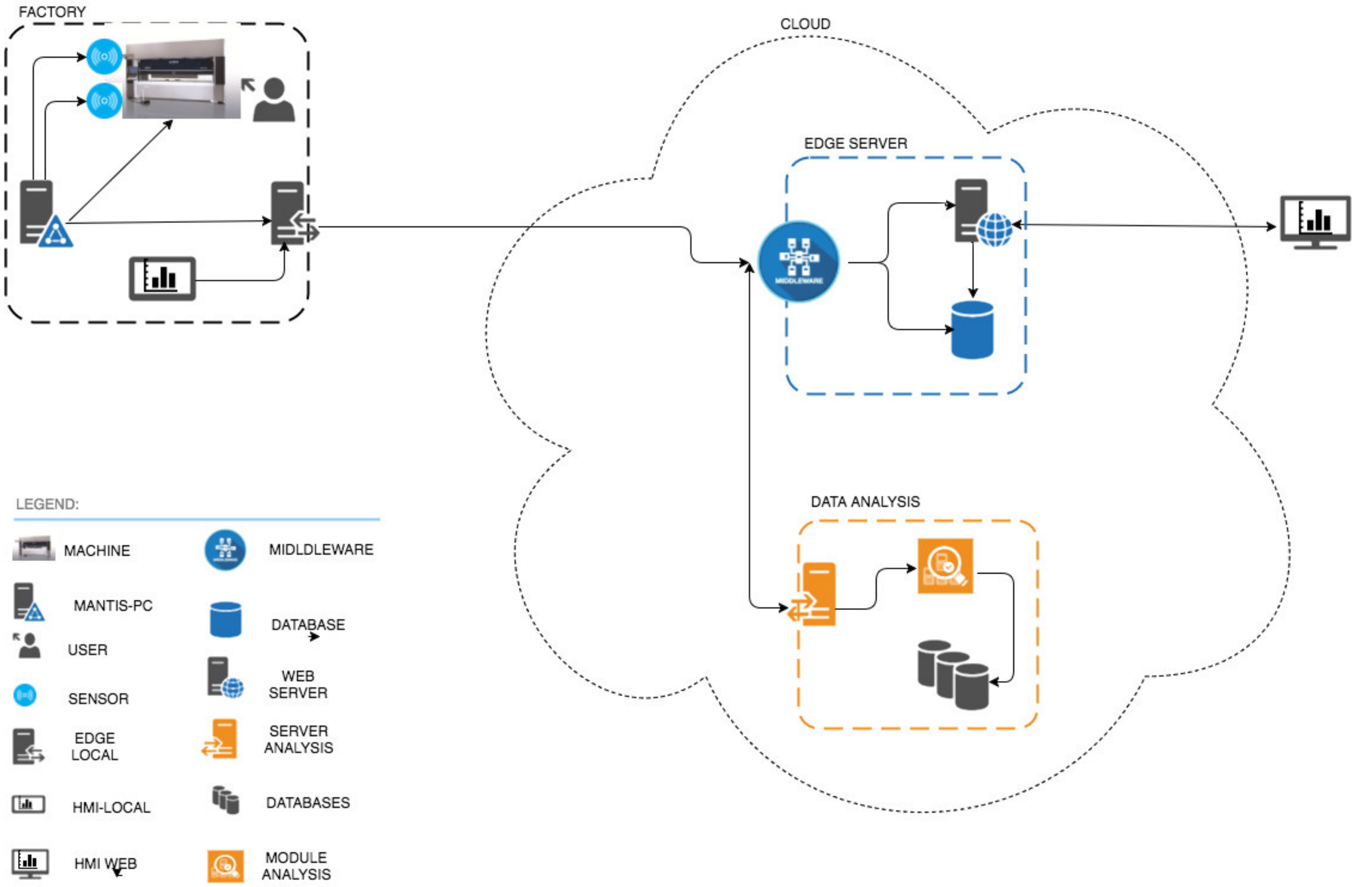
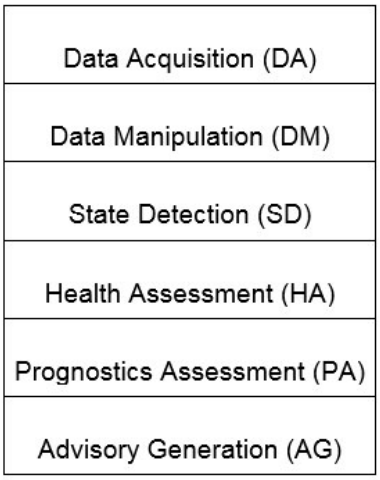


Fig. 2. CBM architecture for the ADIRA case study.

TABLE 1. OSA-CBM Functional blocks [26].



Data Acquisition (DA)
Data Manipulation (DM)
State Detection (SD)
Health Assessment (HA)
Prognostics Assessment (PA)
Advisory Generation (AG)

VI. ADIRA case study

This section describes a case study that applies the envisioned approach to CBM, where sensors are used to monitor an industrial machine, collect and transmit data by means of an efficient middleware, and processes the data in the cloud.

The case study described in this section was actually implemented in the context of the European project MANTIS [14], which aims to apply advanced maintenance techniques to industrial machines by means of the techniques explained in this paper.

The Greenbender (Fig. 2) [26] is a metal sheet bending machine commercialized by ADIRA. This machine is a hybrid system that is powered both hydraulically and electrically, and is controlled via a fluid pumping sub-system. The hydraulics drive two pistons located on a pair of beams that serve as actuators. These actuators move a ram vertically up and down onto a die that is fixed on the machine's base. The ram holds a punch. The workpiece is placed between the punch and the die, acting as clamps, so that it can be deformed.

The architecture for the CBM solution here is depicted in Fig. 3, which is divided into two main parts. One part is the local network hosted on a machine within the factory, and the other part being in the cloud, and which exposes an interface towards the Human-Machine Interface (HMI), accessible via the internet. The architecture is a direct result of the approach designed in this paper, and in fact its first part chases the objectives of collecting data by means of novel sensors driven by advanced CPS, and the second part supports cloud data processing, with all data modeled using ontologies that are derived by the MIMOSA/OSA-CBM Meta model.

A. *Factory local components*

The components that build the local part of the solution are the press brake machine, the MANTIS-PC, the Edge local, and a local, restricted capability, HMI. The press machine (apart from being the target of the monitoring actions) comprises of several data sources: some of them pre-existing such as a Computer Numerical Control (CNC) and a Safety Programmable Logic Controller (PLC), and some that were specifically added for the maintenance platform. The latter includes for example Arduino-based motes with accelerometers that monitor the bending blades for both acceleration, and vibrations.

Fig. 1. The Greenbender machine, featured in the ADIRA case study

The *Edge Local* component provides mechanisms to support communication and management of the data acquired across multiple heterogeneous and distributed data sources using the OPC-UA protocol. It acts as the OPC-UA client in the interaction with the OPC-UA servers located on the *MANTIS-PC*s. This component is meant to be unique in each factory, and it performs pre-processing of the collected data, and it poses the only connection towards the Cloud. This connection to the cloud is done by using the AMQP protocol.

Meanwhile, the *Local HMI* is a simple application that allows the user to view and monitor both the raw data collected in the factory, and the pre-processed information computed by the Edge Local.

B. *Components within the cloud*

The components deployed onto the cloud take care of the data after they leave the factories. The *Edge Local* component of each factory sends data to the cloud, which manages and transports them (*Edge Server* component), process them (*Data Analysis* component) and visualize them (*HMI* component).

The *Edge Server* component is located in the cloud, and comprises of a i) Middleware, ii) a Database module, and iii) the communications server for the HMI. The primary purpose of this component is to feed data to other components in the cloud. In here, the Middleware manages the data stream from the factories, by storing and transporting data between the *Edge Local*, the *Data Analysis* and *HMI* components. The Middleware is message-oriented and is built over an AMQP messaging bus server. The Edge Local afterwards, saves received data on the Database (DB) Component, which is structured according to the MIMOSA/IoT-A standard.

The *Data Analysis* component comprises a set of three modules. The first one is a set of Prediction Models, which are used for the detection, prognosis and diagnosis of machine failures. The models can be built specifically for a machine family or can be generic, and further adapted to different machine families. The second module is the Prediction Application Programming Interface (API), which allows clients to request predictions from the models at a given point of time, and provides data to feed and train the mathematical or machine learning models involved. The last module is the Intelligent Maintenance Decision Support System (IMDSS), which is used to manage the models (model generation, selection, training and testing), for example on the reception of training data or when the API is contacted.

The *HMI* component supports data visualization and system management. The HMI allows to view historical and live data as it is received from the *Middleware* and inspect the results from the *Data Analysis* component, (alarms for unusual data, warnings of impending failures, etc).

VII. Business Model Analysis

The application of new technologies such as new sensors, CPSs and cloud technologies is stimulating an enormous change in how CBM can be taken in everyday use in the industry, even in Small or Medium Sized Enterprises (SMEs).

In the forefront of this introduction of new technology is the manufacturing industry that produces intelligent production machinery. There are several reasons behind the lag on the adoption of predictive maintenance across industries:

Production systems complexity: the majority of industrial facilities are shaped by very heterogeneous assets. This results in the end user's incapability to gather deep knowledge about the behavior of every asset.

Lack of interoperability among different devices or assets: asset manufacturers often apply vendor lock-in solutions to their products to prevent third party modifications. This results in a huge Information Technology (IT) integration work required to connect them, usually preventing end users from implementing predictive maintenance solutions.

Non-reliable prognostics estimates at the system level: even though successful prognostics applications have been deployed at component and sub-system level, asset end users' interest focuses on increasing the availability of the whole system. Thus, the lack of real prognostics and health management systems demonstrated at industrial level derives in a reluctance in early adopters.

In order to overcome these limiting factors, there is a clear need to bring together all value chain actors. For example, within a simple scenario, there has to be the capability of gathering real-time data during production, asset-specific knowledge and analytics expertise.

Beside all of these concurrent knowledge requirements, several non-technological challenges (may even reach out to factors as corporate culture) prevent the penetration of predictive maintenance technologies across industries. The implementation of such a CBM system from scratch (implying the investment in data acquisition, communication and analytics technologies) is not a short-term plan, yet involves great risks. It also supposes very specific knowledge, not available by default.

Partners	***Key Activities***	***Value Proposition***	***Customer Relationships***	***Customer Segments***
Distribution networks ADIRA agents Coordinated supply chain actors	Technological Definition of the most critical failures of each type of production assets which shape the manufacturing lines, classifying them by criticality, frequency & detectability Identification of data (production, process, quality and machine health) though which previous failure could be predicted. Working on the interoperability of each one of the technologies, in order to be able to cope with different shop-floor IT systems: ERP, MES, SCADA, CMMS, etc.	As machine-tool provider (including both machinery –HW- and simulation software packages –SW-) ADIRA has shaped its customer service by empowering a competent and multitalented technical team, being able to support sold machines at every moment throughout their lifecycle.  As shown within the image above, ADIRA provides: Maintenance contracts Preventive maintenance plans, as well as corrective maintenance actions in case of needed Upgrades and retrofits of machinery Spare parts and accessories through its wide distribution network Advanced training packages	Personal assistance through main customer services contact points (after, sales, fairs, etc.) Dedicated personal assistance to premium customers Automated services (just in very standardized machinery solutions) Communities such as the European Association of the Machine Tool Industries associations (CECIMO) Co-creation (agreements with potential customers for new products & services development)	By product type: *Press brakes* *Laser machines* *Shears* *Software packages* By region: Europe America Asia Africa

Fig. 2. ADIRA current maintenance business model

However, for companies assessing the shift to CBM, the following rationale should be considered on the challenges in the introduction of the new technologies: i) Competition and beat-to-market behavior; ii) potentially huge investment in technologies currently unknown to the core business profile, with unforeseeable ROI; iii) the whole business model might have to be reconsidered, with new CBM-based services.

In addition, it is important to understand the security issues connected with the use of IoT and the cloud computing, especially in the case when the data is stored and transmitted outside the company domain, which makes it more vulnerable. The reason is, as mentioned earlier, that many of the existent security solutions are not applicable in the case of the new emergent ICTs such as the cloud computing as well as the CPS. It is, however, crucial to have a clear understanding of the different threats that such systems might experience, i.e. their vulnerabilities and consequences. In addition, it is vital to comprehend the emergent ICTs unique characteristics, namely how they differ from the traditional or current systems for purposes of using proper security solutions as well as optimizing their use. There are, however, efforts and developments by the industry as well as academia to meet those new challenges that the emergent ICTs bring.

Within the ADIRA case study, we have performed a business model transformation to enable advanced maintenance services, based on CBM:

- Shifting from products to services through vertical integration such as after sales and offering software solutions, or consulting services.
- Further, increase already strong level of internationalization through intensified local value creation and shorter time to market (TTM).
- Assess new revenue sources and design new business models such as pay per use or platform.
- Use digitization to improve production costs.
- Build capabilities in business development and sales to identify and implement new business models.

Figure 4 depicts the actual business model for the case study. Once having defined the Product Marketing Manager (PMM) business models framework, it's identified who are the successful players and technologies that have already penetrated the market. Special attention has been paid to product plus service business schemes, as well as to the technology vendors with most mature platforms. Thus, current and future business models related to PMM of MANTIS industrial partners can be assessed, stating from a qualitative perspective how these new technologies will change the business landscape at corporate local level.

The achievement of those specific objectives will be performed aligned with several workstreams: Servitization trend

<table>
<tr>
<td rowspan="2">*Key Partners*
Data collection
Communications
Prognostics
Decision Support
After sales services</td>
<td>*Key Activities*
System design
CNC Machine monitoring
Sensors installing
Algorithm upgrading</td>
<td rowspan="2">*Value Proposition*
As a result of MANTIS, ADIRA's new product ranges will include the following smart features:
▪ **Data acquisition technologies:**
▪ Oil quality sensor: low cost sensing element for oil condition monitoring
▪ Sensor for acceleration measurement of the crankshaft: this system has multipurpose capabilities, able to collected information from accelerometers and transmit that wirelessly to an edge computer, using Bluetooth Low Energy.
▪ Implementation of the Middleware for data acquisition: based on Rabbit MQ and capable of collecting data on ADIRA's machines and transmitting it to the cloud
▪ Machine's internal data acquisition module: this software module acquires data from the CNC controller shared memory containing information about some of the machine sensors
▪ **HMI for sheet metal machinery:** capable of showing maintenance information related with Portuguese pilot use-case: Historical data, machine malfunctions and events.
▪ **Analysis and decision making functionalities:**
▪ Remaining Useful Life estimation method: Combination of data preprocessing, data transformation and (supervised) machine learning algorithms used for RUL estimation.
▪ Root cause analysis method for sheet metal working machinery: Combination of data preprocessing, data transformation and (supervised) machine learning algorithms used for root cause analysis (RCA).
▪ Alerting and prediction of assets failure for the sheet metal machinery: Combination of data preprocessing, data transformation and (supervised) machine learning algorithms used for failure detection.
▪ Maintenance optimization for the sheet metal machinery maintenance services: Optimization models used for the scheduling of the maintenance tasks using RUL estimation.</td>
<td>***Customer Relationships***
Key account management activities
New marketing campaign strategies</td>
<td rowspan="2">***Customer Segments***
Already sold machinery (offer upon existing production assets):
Premium customers *(new services to assure customer loyalty)*
Medium priority customers *(boosting strong relationships and new revenue streams)*
New machinery projects
Premium customers: lower prices to maintain customer loyalty,
Medium priority customers: extended machinery functionalities, being able to opt to higher quality market segments based on advanced services associated to machinery.</td>
</tr>
<tr>
<td>***Key Resources***
Factory level Service Bus and decision support
ADIRA's cloud
MANTIS Cloud
HMI</td>
<td>***Channels***
Traditional sales channels
Machine tool trade fairs (e.g. Hannover Messe, EUROBLECH, etc.)</td>
</tr>
<tr>
<td colspan="3">***Cost Structure***
Manpower (fixed and variable labor)
Travel expenses (travel & accommodation)
Technology (IT, Telecom, logistics, etc.)
Facilities (rental, maintenance, utilities)
Spare parts (other suppliers, in house capabilities)
Call centre (outsourced and/or integrated within the company)
Equipment (new purchasing, upgrading, depreciation, etc.)</td>
<td colspan="2">***Revenue Stream***
The revenue streams will follow the product-service models towards the machine tool industry is moving:
Revenue due to service (*high margins*):
- Licenses of data aggregation software
- Licenses of data pre-processing & analysis software
- System level model building and algorithm fine-tuning
- Alert generation, supply chain management, manufacturing recommendations, maintenance scheduling, etc.
Revenue due to product (*low margins*):
- Additional measurement technologies deployment (hardware)
- Local pre-processing & analysis system
- Ad-hoc HMI at machine, CMMS, ERP or cloud level
- Implementation of secure communications along the manufacturing line</td>
</tr>
</table>

Fig. 3. ADIRA PMM enabled business model

analysis regarding the different MANTIS value chains. Depending on the representatives of each value chain (there is a wide range of partner profiles along the maintenance value chain within the MANTIS consortium), different business models are drafted.

- The commercial maturity of approached product and services: depending on the targeted industrial sector, technology is definitely not a newcomer (e.g. wind energy equipment monitoring). Thus, the definition of the service business state-of-play and how industrial partners foresee to change (in a medium term) will also help to determine to what extent each solution has overcome early sales barriers; and which is actually the potential of technologies presented in this paper.
- Market penetration of such after sales services: even though sectorial aspects do largely influence the commercial maturity, some companies have performed better than others regarding revenue consolidation. Extracting information from entities' annual reports, the weight of after sales services upon total revenue can be easily observed.

Figure 5 shows the result of adapting the old business model into a PMM based business model that monetize the data generated by their machinery through the implementation of advanced services.

VIII. Conclusion

The paper describes the concept of CBM and CPS and how they are integrated together with the cloud computing in a maintenance system. Implementing a CPS will lead the industry to have more information on the monitored assets and, thus, more control over them. Not only this will help to reduce the downtime and increase the OEE, but it will also help the designers to create better equipment if the weak points are known. The new technologies such as MEMS sensors and the drop in the price of high processing power enable this type of maintenance strategy to be growing more popular. This, at the same time, allows the creation of new tools for the said strategy, such as more powerful sensors or specific analytics software on top of state of the art standards and technology. Current trends suggest that the price of these devices is going to keep decreasing in the near future. Taking a look at the evolution of the industry, there is a high chance that the CPS are going to become a must in the sector. Data processing done by means of cloud-based advanced techniques can provide an edge for the implementation of CBM, and this is enabled by means of robust data models, and open standards.

Novel techniques are being experimented with by using demonstrators and pilots applied to real scenarios, speeding up innovation and proving the technological and economic potential of CBM for all the involved. In summary, the implementation of such a system will help increase the automation of the plant while carrying out the maintenance with as little disruption as possible and improve the design of the equipment.

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