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Condition-based maintenance implementation: a literature review

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Abstract

Industrial companies are increasingly dependent on the availability and performance of their equipment to remain competitive. This circumstance demands accurate and timely maintenance actions in alignment with the organizational objectives. Condition-Based Maintenance (CBM) is a strategy that considers information about the equipment condition to recommend appropriate maintenance actions. The main purpose of CBM is to prevent functional failures or a significant performance decrease of the monitored equipment. CBM relies on a wide range of resources and techniques required to detect deviations from the normal operating conditions, diagnose incipient failures or predict the future condition of an asset. To obtain meaningful information for maintenance decision making, relevant data must be collected and properly analyzed. Recent advances in Big Data analytics and Internet of Things (IoT) enable real-time decision making based on abundant data acquired from several different sources. However, each appliance must be designed according to the equipment configuration and considering the nature of specific failure modes. CBM implementation is a complex matter, regardless of the equipment characteristics. Therefore, to ensure cost-effectiveness, it must be addressed in a systematic and organized manner, considering the technical and financial issues involved. This paper presents a literature review on approaches to support CBM implementation. Published studies and standards that provide guidelines to implement CBM are analyzed and compared. For each existing approach, the steps recommended to implement CBM are listed and the main gaps are identified. Based on the literature, factors that can affect the effective implementation of CBM are also highlighted and discussed.

Keywords: Condition-Based Maintenance (CBM); Condition monitoring (CM); Prognostics and Health Management (PHM).

1. Introduction

Industry is experiencing growing challenges caused by increasing customer demands and highly competitive business environments [1]. To enable inventory reduction, delivery times became substantially shorter. Thus, disruptions in production flows are quite critical. In more demanding business environments, malfunctions, speed losses and erratic performances of relevant equipment can impede timely delivery of products and services [2]. Moreover, automation level and immobilized capital in fixed assets is increasing across all industries. The investment in advanced equipment contributes to enhance companies' productivity and to reduce the labor cost. Therefore, the ability to effectively preserve equipment condition is crucial to meet the organizational objectives.

Due to rapid technological innovations, industrial systems are gradually becoming more complex. In general, a production system is composed of a wide range of equipment which operate interdependently. Each piece of equipment can comprise numerous components with different physical and technical characteristics. Regardless of their nature, physical asset are subject to one or more natural processes, such as wear, corrosion, oxidation, etc. [3]. Nevertheless, the degradation rate of the equipment condition is greatly influenced by the usage time and operating conditions, namely atmosphere, intensity and load [4].

The global modernization effort originated by Industry 4.0 furthered the development of Information and Communication

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Technologies (ICT). Hence, the technologies underlying Internet of Things (IoT) and Cyber-Physical Systems (CPS) are becoming more prevalent in companies [5]. Nowadays, industrial equipment often includes embedded measuring devices which allow to collect a wide variety and large volume of operating data in real-time. Alternatively, customized data acquisition systems can be established using adequate sensors or testing devices. If the data are appropriately selected and analyzed, it is possible to obtain information about the equipment condition. Afterwards, this information can be used to define accurate and timely maintenance actions.

A common objective of companies is predicting irregular behaviors that can affect the performance of their equipment, tools and processes, in order to undertake actions to prevent accidents and economic losses [5]. Future state predictions can be made considering equipment current condition and historical data. However, the direct observation of data provided by sensors or testing devices generally does not allows to infer the condition of a system or component. The information to assess the current condition and predict future behavior usually results form a complex process which involves preparation, transformation and modelling of the original data, concerning one or more relevant variables. For this purpose, different theories and techniques for data analytics can be adopted and combined [6]. Moreover, the efficient and continuous application of Condition Monitoring (CM) requires an adequate maintenance strategy for identifying problem areas and relevant information; acquiring, managing and analyzing data; decision-making; planning and executing maintenance tasks cost-effectively [7].

Over the last years, the need to develop more research related to Condition-Based Maintenance (CBM) implementation and management has been advocated by several authors. Furthermore, various limitations in the existing literature are highlighted. According to Jardine *et al.* [8], the development of robust approaches to perform failure diagnostics and quick and accurate approaches for prognostics is a priority area of research. Peng *et al.* [9] advocate that priority should be given to comprehensive methodologies in the prognostics domain instead of specific models, to facilitate the adaptation to rapid changes in industry. These authors also emphasize the importance of defining criteria to assess and compare the accuracy and precision of prognostics algorithms. Lee *et al.* [10] highlight the need for a systematic methodology to develop and implement Prognostics and Health Management (PHM) systems, which enables the quick integration of the systems in different contexts. The absence of an holistic approach for PHM application is also emphasized by Tsui *et al.* [11] and López *et al.* [12]. Prajapati *et al.* [13] argue that a standard and adaptable CBM architecture to ensure interoperability is required. In turn, Guillén *et al.* [14] underline that methodologic structures for CBM/PHM should go beyond the technologic aspects. Thus, management issues must also be considered to ensure higher efficiency [7,14,15].

The successful implementation of CBM assumes great importance, due to the high expenses involved. According to Guillen *et al.* [14], the complexity of the new CBM programs hinders their effective implementation in large scale in industry. Rastegari and Bengtsson [16] advocate that the use of an adequate implementation approach can increase the chances of success and the return on investment. For this purpose, it is crucial to understand how to conveniently apply the CBM methods and to control their implications in a sustainable and efficient manner [14]. Al-Najjar [7] underlines that the absence of concrete procedures to establish CBM generates confusion between CBM systems and CBM policies. Moreover, this author also considers that the lack of systematization in the establishment and administration of CBM impedes the assessment, control and tracking of its technical impact and economic contribution.

Due to the complexity involved in CBM activities, it is crucial to obtain appropriate orientation to support the implementation process. Thus, implementation approaches are needed to facilitate the adoption of CBM by companies and enhance the chances of success. In this paper, a literature review about CBM implementation is presented. The paper is organized as follows. In section 2, a description of CBM and related concepts is provided. Section 3 provides a general overview of the steps involved in a CBM program, analyzes the approaches for CBM implementation identified in the literature and presents some concluding remarks. Finally, in section 4 the main conclusions of the literature review are derived.

2. Condition-based maintenance

CBM is a subtype of preventive maintenance and it is frequently classified as a maintenance strategy. The main purpose of CBM is to recommend maintenance decisions based on information obtained through CM [8]. Therefore, the effectiveness of CBM decisions depends of the monitoring process accuracy [17]. According to Guillén, *et al.* [14], CBM aims to control equipment failure modes. Thus, when CBM is established, all potential failure modes that can result in economic losses should be considered [7]. CBM relies on the assumption that most failures do not occur instantaneously, and it is possible to detect their appearance at an early stage of the deterioration process. The main challenge is to determine the exact moment in which maintenance should be performed and identifying the most appropriate action [18]. P-F curve (Fig. 1) can be used to represent the Remaining Useful Life (RUL) of a component, considering a specific failure mode [19].

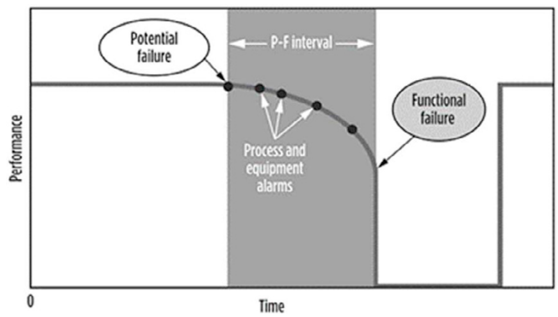

Fig. 1. PF curve (source: adapted from Snider [20]).

The P-F curve depicts the performance or condition evolution of the monitored component between the instant in which a potential failure can be identified (P) and the instant wherein the consequential functional failure is verified (F).

Thus, the time available for performing an appropriate maintenance action is limited to this interval [13]. However, it should be considered that failure mode progression is often influenced by changes in operations, maintenance actions or by the occurrence of other failure modes [21].

Degraded faults are usually preceded by a gradual performance decrease of the affected component [22]. In this case, CBM application allows components to be used while they can achieve the desirable performance level. Thus, repair or replacement of a particular component are performed only when the measured performance is lower than a predetermined limit [13]. This limit is usually named warning limit and can be determined with respect to a single variable or a combination of variables [23]. It is often defined based on experience, analysis of past data and recommended standards [24]. When optimization models are used to represent the deterioration process of a given component, the warning limit is usually a decision parameter of the model. The corresponding maintenance action is planed only if the deterioration level exceeds the warning limit. Therefore, the application of CBM requires a dynamic planning of maintenance actions [15,25]. Failure occurs after a certain deterioration level is reached (failure limit). However, in practice, the deterministic failure limit cannot always be determined with the desired accuracy.

Preventive replacement of critical components in predefined intervals to prevent the effects of an eventual failure is a common practice in many companies. However, the adoption of this policy leads to the waste of a portion of the replaced components' useful life. Furthermore, it has a negative environmental impact [24]. In this context, the ability to accurately predict the residual life and the reliability of a system, provides relevant information to plan maintenance actions with a lower cost. To this end, a predictive model that triggers a warning early enough to perform the necessary maintenance action before the failure occurs must be developed [9]. This strategy is usually named predictive maintenance.

According to Guillén *et al*. [26], predictive maintenance is an integral part of a broader concept of CBM which resulted from the progressive introduction of new resources to support the maintenance function, such as skills, technologies, techniques and methods. The concept of PHM is also frequently used in CBM domain. PHM was first introduced in the aviation program for Joint Strike Fighter development promoted by the United States and allied countries. Since then, PHM was adapted to several industries [27]. The main purpose of PHM is to preserve integrity and hinder irregular behaviors. In this context, prognostics is the process to predict the RUL of a system or component considering the degradation level, load history and expected operation conditions [28]. Whereas health management is a process to establish and apply appropriate and timely maintenance actions and make logistics decisions based on the diagnostics and prognostics results. To this end, the available resources and operational requirements must be considered [10]. According to Elghazel *et al*. [29], PHM involves the same steps as CBM. Guillén *et al*. [26] outline that PHM represents the set of tools that allow to generate maintenance decisions. These tools can use data obtained based on CBM techniques [10]. Thus, the PHM tools allowed to expand the CBM concept. The development of Condition-Based Maintenance Plus (CBM+) strategy also contributed to the evolution of CBM. CBM+ is a broad strategy established in 2002 by the Deputy under Secretary of Defense for Logistics and Material Readiness of the United States. It aims to optimize CBM application based on the Reliability Centered Maintenance (RCM) analysis. CBM+ was developed to perform a continuous or periodic assessment of the weapons system condition using sensors or external tests and measurements through direct observation at first hand or portable equipment, seeking to ensure that maintenance is performed only when it is needed (DoD, 2008).

The impact of maintenance decisions depends on the moment in which the maintenance action is performed. According to Guillén *et al*. [26], CBM supported by PHM resources is the maintenance strategy that allows to perform more timely maintenance actions. Therefore, its associated value is higher. However, Lee *et al*. [10] highlight that the adequacy of maintenance strategies depends on the complexity and uncertainty associated with the system to be maintained. These authors present a map which organizes different maintenance strategies according to the complexity and uncertainty associated with the system. The proposed scheme shows that CBM can be applied to deterministic systems, static to certain extent, and in which condition can be represented by variables of low dimensionality that constitute system health indicators. Whereas PHM should be applied to systems that operate in probabilistic and static conditions, and which involve a high number of variables, when intrusive approaches can be used [10].

Although CBM objective is to perform accurate maintenance decisions, this purpose is not always easy to accomplish due to the operating environment, equipment internal structure and hidden failure mechanisms [15]. Thus, Al-Najjar [7] underline that probabilistic modelling of time to failure must be used as a complement to CBM deterministic methods in order to increase decision making effectiveness. CM data provide information to short term predictions, whereas the reliability data allow to extended predictions until the next maintenance window [29].

3. Condition-based maintenance implementation

CBM implementation usually requires the selection of the components to be monitored, identification of monitoring techniques and technologies, installation of the required technological means and definition of appropriate data analysis methods [16]. Therefore, the investment involved can be considerable. The main expenses include the acquisition of measuring devices, hardware and software, and the provision of specialized knowledge and training [6,31]. Thus, the feasibility of CBM implementation should be analyzed considering the organizational, financial and technical perspectives. Niu *et al.* [15] highlight that the feasibility of investments related to CBM should consider the equipment importance, their technical characteristics and the external environment complexity. According to Al-Najjar [7], technical justification that demonstrates the ability of CM systems and CBM policies to achieve the strategic objectives of the company must be provided.

When CBM is adequately planned, it contributes to enhance the overall performance of maintenance function [31,32]. However, Shin and Jun [31] and Hwang *et al*. [33] emphasize that the benefits of CBM implementation are higher when CM is performed in an integrated manner at the system level.

3.1. CBM process

The CBM process can be described based on a sequence of generic steps. Ahmad and Kamaruddin [18] identify two basic steps: CM and decision making. According to Jardine *et al.* [8] and Lee *et al.* [10], CBM involves data acquisition, data processing and maintenance decision-making. This depiction is widely accepted in the literature, although some variants exist. ISO 13374-1 (Condition monitoring and diagnostics of machines – Data processing, communication and presentation – General guidelines) organizes condition monitoring assessment in six functional blocks, such as data acquisition, data manipulation, state detection, health assessment, prognostics assessment and advisory generation. This standard establishes the basic requirements for open software specifications, to facilitate the obtention, transmission and utilization of condition data. The first three blocks are focused on a specific technology, whereas the final three usually attempt to combine monitoring technologies [34]. Each block should be defined independently [35]. Peng *et al*. [9] present a framework for representing the CBM process. The presented framework shows general steps to convert sensor data in information for maintenance decision making. This is a simple representation which aims to point out future research directions in the CBM domain. However, the focus of this research is the analysis of prognostics methods for CBM. Additional examples of steps to perform CBM can be found in Elghazel *et al*. [29] and Lei *et al*.[36]. Although the presented steps are common to most CBM processes their requirements for each application can be substantially different. Thus, to achieve accurate outcomes and ensure cost-effectiveness, the CBM process must be designed, implemented and executed considering the objective of each application, functional constraints and interdependencies between the individual steps. A general description of the CBM process, considering the data acquisition, data processing and maintenance decision-making steps, is provided below.

Data acquisition: It involves the capture and storage of data related to variables which can reflect the degradation process of the components to be monitored [13]. For each variable, the relationships to the equipment failure modes should be identified [19]. Furthermore, the selection of measuring devices must consider the nature of the variables to be monitored [28]. CBM makes use of event data and monitoring data. Event data are useful to assess the performance of condition indicators and to support improvement actions or refining the indicators established previously [8]. In general, event data related to critical assets are scarce or inexistent because their failure must be avoided [36]. Therefore, the monitoring data are an important source of information [24]. These data are usually classified into three categories: numeric, wave and multidimensional [6,8]. If the data collection is performed continuously, higher storage capacity is needed. Therefore, it is advisable to define the data collection intervals according to each specific circumstance. Furthermore, the most advantageous data transmission solution in terms of cost and reliability should be identified [31].

Data processing: It aims to extract important information from the data to support maintenance decisions [29]. Data processing involves data cleaning and analysis [8]. Data cleaning is required, since the data are often unstructured and imperfect [37]. Errors or imperfections in the data can be caused both by sensor faults and human factors [8]. To perform data analysis, appropriate methods and software should be identified [13], depending on the data type. The processing of wave and multidimensional data is designated as signal processing. Whereas the procedure to extract useful information from original signals is named feature extraction. The features extracted based on signal processing can be represented in the form of numerical values [8]. The obtained features can result from the combination of other features [38] and should provide a proper representation of the system health condition [39]. Often a single sensor is not enough to collect data to correctly analyze the condition or predict the future behavior of an item. In this case, the data collected by sensors installed in different locations should be combined. This procedure is designated as data fusion [8]. Data fusion can be performed at three different levels: original data, feature and decision making level [15].

Maintenance decision-making: It requires a detailed analysis of the information resulting from CM to decide whether it is necessary to intervein in the equipment, which is the most appropriate maintenance action (e.g., inspect, repair, replace, etc.), and when and how maintenance should be performed [14]. CBM decisions can be supported by a great variety of methods that enable to estimate the current condition or predict the RUL of a specific component, namely data driven methods and physical models [21]. Current condition analysis and future condition prediction are usually represented by the concepts of diagnostics and prognostics, respectively. Diagnostics is associated with failure detection, isolation and identification [8,9,29]. Whereas prognostics aims to predict failures before they occur, allowing the early scheduling of interventions. The information resulting from failure diagnostics can be useful to refine the prognostics and to introduce improvements in the system [8]. Thus, diagnostics should be performed continually in order to detect new events and update the prognostics estimates. However, monitoring failure progression can involve different parameters from those used in diagnostics activities. Therefore, it should be determined how the physical system and the observed parameters are interrelated [21]. For this purpose, knowledge or data about the failure propagation and failure mechanism are required [8].

3.2. Approaches for CBM implementation

Architectures and frameworks: CBM programs can be extremely difficult to manage, due to the need of dealing with a great amount of information that changes over time and exhibits complex relationships [14]. To overcome this issue, architectures and frameworks for CBM management are proposed in literature. The analysis of these structures may provide useful information to support CBM implementation. Nevertheless, they do not define activities for implementing CBM. The Open Systems Architecture for Condition-based Maintenance (OSA-CBM) specification provides a standard architecture for moving information in a CBM system. It includes data structures and defines interface methods for the six functionality blocks defined by ISO 13374 [35]. Some insight for CBM management can also be found in the CBM+ DoD Guidebook [30] and ADS-79D-HDBK handbook [42] which describes the Unites States Army's CBM system. Concerning academic literature, Niu *et al.* [15] developed a CBM system that applies RCM to optimize the cost of maintenance and employs data fusion strategy to monitor the equipment condition and perform diagnostics and prognostic activities. The CBM system is composed of three main blocks: RCM, CBM and data fusion. RCM is used to identify vital components, potential failures and appropriate maintenance tasks. Afterwards, cost analysis is performed considering the selected tasks and the maintenance intervals derived from experience. The CBM system is based on the OSA-CBM architecture and it is recommended to be applied when CBM is more appropriate than corrective maintenance and predetermined maintenance. It involves data acquisition in real time using several sensors. The information about the equipment condition is obtained based on features extracted after signal processing. The features that enable to detect failures are selected to perform diagnostics, whereas features that indicate a degradation trend in the equipment condition are considered for RUL prediction. To provide a more precise and reliable monitoring, the fusion of multiple degradation indicators is proposed. According to the process developed for integrating the system and the data fusion techniques, the definition of appropriate maintenance actions should be supported by the results of CM, diagnostics and prognostics. The proposed system was applied in two case studies: decision-level fusion for an induction motor fault diagnostics and feature-level fusion for a compressor CM and prognostics. This research defines a general framework to depict an overall maintenance program and proposes an architecture to organize CBM system when remote data acquisition systems are available. However, CBM is addressed only from a technical point of view and no formal procedure to support CBM implementation is provided. For this purpose, guidelines and tools to facilitate the definition and application of the different elements included in the CBM architecture and to assess cost-effectiveness are required. Moreover, this study does not specify how to select appropriate technologies for data acquisition and transmission, and data analysis techniques. Guillén *et al*. [14] developed a structure that represents and characterizes the fundamental elements of a CBM program life cycle, and a form based on RCM analysis to integrate the information related to each failure mode. This study establishes a formal and uniform treatment to ensure the inclusion of relevant aspects in each CBM solution, appropriate knowledge management, and scalability and replicability of CBM applications. The proposed framework is composed of five blocks: physical description, functional description, information sources, symptoms analysis and decision making. Each block represents a perspective or technical area which should be considered in the application of a CBM model and was defined according to reference methods and standards of its respective domain, namely ISO 13374 and OSA-CBM. The management of information associated with each block can be performed using individualized software systems. The physical description and functional analysis allow to relate CBM to the RCM perspective and define the failure modes. The remaining structure is established considering the identified failure modes. Unified Modelling Language was used to represent the different elements of the structure and their relationships. The framework was tested in the prognostics of a power transformer failure mode based on risk estimations performed in real time for the selected failure mode. Although this research presents relevant concepts that should be addressed to define a comprehensive CBM solution and their relationships, its contribution is merely theorical. Thus, to develop a specific application practical knowledge on each concept is required and an appropriate implementation procedure must be developed by the user to establish the individual blocks.

Methodologies: The methodologies and procedures to implement CBM identified in the literature are described below and summarized in Table 1, presenting their steps.

Table 1. Sequential steps for the implementation of CBM or PHM.

Author	Steps for CBM or PHM implementation
Starr [40]	Criticality survey; maintenance audit; select units; match technique to failure mode; routine monitoring; assess technique and assess cost effectiveness.
Al-Najjar [7]	Identifying problem areas; identifying significant components; identifying damage causes and development; identifying relevant CM systems; technical justification; selecting the most informative CM system; deciding a suitable measuring system and policy; deciding data gathering route; determining normal, warning and replacement levels; data analysis; presentation of analysis results; scheduling maintenance actions; reparation for doing maintenance tasks; assessing the human resources needed; assessing technical and economic impacts; measures to follow up changes in maintenance performance; identifying maintenance role.
Rastegari and Bengtsson [16]	Concept study; define responsibilities; selection of assets; selection of techniques and technologies; installation; data handling; training; measurement and setting baseline data; data analysis; evaluation; improvement.
López *et al*. [12]	Preparatory task and implementation plan; determination of asset hierarchy; RCM analysis of critical equipment; signals and detection methods assignment for critical failure modes; algorithms to support making-decision; transferring results to the maintenance plan and business indicators; following the efficiency and effectiveness of maintenance.
Lee *et al*. [10]	Streamline (select critical components, sort, filtering and prioritize data); smart processing (select features and tools); synchronize & see (select the hardware and information visualization); standardize (select the interface and connectivity) and sustain (select management tools and value chain).
ISO 17359 [41]	Cost benefit analysis; equipment audit; reliability and criticality audit; select appropriate maintenance strategy; data acquisition and analysis; determine maintenance action; review.

Starr [40] presents a procedure to implement CBM which contemplates the selection of equipment to be monitored and monitoring techniques for failure prediction. The equipment selection should be made considering the results of a criticality analysis and supported by a maintenance audit aimed at prioritizing areas in which cost savings can be most significant. To perform criticality analysis, the author recommends the application of Fault Tree Analysis (FTA), Failure Mode and Effect Criticality Analysis (FMECA). After the equipment selection, the most relevant failure modes should be identified based on the equipment failure history and monitoring techniques must be chosen to match the failure modes. According to the author, the failure modes may be ranked using a Pareto chart considering the associated frequency and downtime. This procedure requires regular reviews of the selection of techniques, failure modes and plant units considering a cost-benefit analysis. The reviews are intended to refine the previous selection and settings (e.g., monitoring intervals and alarm levels), meet plant modifications, and make decisions on the extension of CBM to other equipment. The presented procedure was applied in two case studies: robots in automated production and a building services plant. However, due to time constraints the application of the review and cost-benefit analysis stages was not completed. Although this procedure includes general steps to guide CBM implementation, it does not provide guidelines for selecting the parameters to be monitored, monitoring techniques, monitoring frequency and data analysis methods, and for setting warning limits. Al-Najjar [7] developed a set of steps aimed at establishing and organizing CBM cost-effectively. The defined approach was not tested in practice, due to the significant resource requirements and amount of time needed for the application. Nevertheless, it was compared to the procedures used by three companies to implement vibration-based maintenance (VBM). After discussing the steps of the procedures used in the companies, the author verified that VBM was not implemented systematically. Moreover, some of the procedures were done subjectively without a scientific basis. Even so, the applications of VBM were considered cost-effective by the companies. Although the approach proposed by Al-Najjar [7] is rather extensive, it is mostly oriented to VBM application and little insight is given on how to perform each step, namely about scientific methods to decrease the level of dependency on the knowledge of experienced staff. Rastegari and Bengtsson [16] defined a work process to implement CBM in companies, considering technical and organizational perspectives. The steps of the work process were defined based on the results from a study intended to support the online implementation of two CM techniques: vibration analysis and shock pulse method. A questionnaire was used to obtain relevant information about the equipment, namely technical characteristics, critical components, failure modes, performance indicators, failure frequency, types of maintenance actions performed, programed actions, production impact, and failure and maintenance costs. Afterwards, the obtained information was considered to define structured implementation approach. Some relevant factors to be considered in the implementation process are emphasized and described by the authors, particularly concerning the techniques applied in the case study. However, they do not indicate how to perform the implementation of each step. Furthermore, according to the authors, the tools and methods used still need to be tested for other industrial equipment. They also highlight that more research should be performed on the applicability of CBM to different types of equipment, techniques and technologies for CBM, and assessment of the cost-effectiveness of CBM in industry. The work process developed by Rastegari and Bengtsson [16] is comparable to the implementation approach presented by Starr [40], although more importance is given to organizational aspects, such as culture needs and competence within the organization. López *et al.* [12] identify a set of sequential tasks to be considered in the development of a practical methodology for implementing a PHM solution. These tasks were defined after a theoretical analysis of complexity factors related to PHM application, namely data treatment, communication and interfaces; high specific technological knowledge; and strategic and holistic view and business value. The authors also recommend using RCM to select the most appropriate equipment items. According López *et al.* [12], this task can be supported by tools and methodologies such as Failure Mode and Effect Analysis (FMEA), Reliability Block Diagram (RBD), Reliability Prediction (RP), FTA and Event Tree Analysis (ETA). Furthermore, for following the efficiency and effectiveness of maintenance the authors suggest the application of the Graphical Analysis for Maintenance Management (GAMM) method. For this purpose, two graphical tools should be developed, namely maintenance interventions performed to a piece of equipment vs. time and level of system reliability when each maintenance intervention is performed vs. time. Lee *et al.* [10] present a systematic methodology for rotary machine systems aimed at converting multivariate data in prognostics information. The methodology includes procedures to identify critical components and tools to select the more adequate algorithms for specific applications. These authors also propose a set of visual tools to exhibit prognostics information for decision-making. The defined methodology is composed of five steps aimed at conceiving and gradually implement a PHM system (Table 1). A four-quadrant chart is recommended to identify critical components. This chart allows to represent components fault frequency vs. the average downtime caused by components. Moreover, it also enables to assess the effectiveness of maintenance policies. The main objective is to determine to which quadrant the relevant components belong. The quadrants definition is based on production and maintenance requirements. Prognostics activities should be applied to components which locate in the quadrant which corresponds to low fault frequency and high average downtime. Lee *et al.* [10] also suggest the use of Quality Function Deployment (QFD) for selecting algorithms to perform signal processing and classification, and to estimate the current and future condition of the equipment. QFD allows to create an ordered list of algorithms associated with each category, considering the data characteristics that determine the suitability of each algorithm. The information resulting from the application of the selected algorithms should be represented using visual tools that facilitate their interpretation, such as degradation chart, performance radar chart, classification and fault map, and risk chart. The proposed methodology and the visualization tools were applied in four case studies: alternator component health assessment, airport chiller, spindle bearing health monitoring and engine risk management. Although this methodology provides useful guidelines to support the PHM implementation, the organizational and economical perspectives are not considered. Furthermore, other tools and procedures should be incorporated to better match the requirements of different application domains. ISO 17359 [41] (Condition monitoring and diagnostics of machines - General guidelines) establishes a comprehensive procedure for implementing a condition monitoring program, which is illustrated in a flowchart. Furthermore, it describes a generic approach for setting alarm criteria and performing diagnostics and prognostics. This standard also provides examples of condition monitoring parameters for a group of ten types of machines in which CM is commonly applied. For each machine, examples of possible faults are matched to measurement parameters and techniques. However, no recommendations to select appropriate data analysis methods to support decision making are provided.

3.3. Concluding remarks

The literature review allowed to identify four approaches that describe steps to support the implementation of CBM [7,16,40,41] and two methodological approaches to assist the development of PHM systems [10,12]. Furthermore, three architectures and frameworks that represent CBM systems were found [14,15,35]. OSA-CBM remains the main reference in this field and it was the basis for the development of two frameworks analyzed in this paper. These structures promote a higher understanding of the concepts related to CBM, nevertheless they do not provide enough information to implement a CBM system. Thus, the use of RCM to systematize the application of CBM is recommended by some of the authors, namely Niu *et al.* [15] and Guillén *et al*. [14].

Concerning the implementation approaches which define procedures found in the academic literature, only the procedures proposed by Starr [40], Rastafari and Bengtsson [16] and Lee *et al*. [10] were applied in case studies. The application in real scenarios provides the opportunity to refine and validate the defined procedures, however it is often hampered by time and resource constraints. This represents an important limitation for research. The proposed implementation approaches rely considerably on technical experience in CBM. This knowledge is not always available in companies and sometimes results in subjective and inaccurate decisions. Therefore, making CBM accessible to a larger number of companies and increasing the benefits of its implementation is a major challenge for researchers.

The literature review showed that some of the most relevant tasks to address in CBM implementation are:

- Selecting components, failure modes and parameters to be monitored;
- Identifying the causes and symptoms of the failure modes;
- Linking the monitored parameters or condition indicators to specific failure modes;
- Identifying and installing appropriate measuring techniques and technologies for the acquisition and transmission of CM data;
- Defining the CM frequency;
- Selecting methods and software to analyse CM data;
- Setting warning limits for the monitored parameters or condition indicators;
- Defining methods and tools to support maintenance decision-making;
- Performing a cost-benefit analysis.

It is considered that the methodology developed by Lee *et al.* [10] is the most relevant contribution to support the execution of the presented tasks in a simple and direct manner. This methodology includes graphic tools for identifying critical components, selecting appropriate methods for signal processing and data analysis, and presenting useful information for maintenance decision-making. However, this work is focused on rotary machinery and does not address the definition of warning limits and monitoring frequencies. Thus, the methodology should be complemented with additional tools and methods. The approaches developed by Al-Najjar [7], Rastafari and Bengtsson [16] and ISO 17359 [41] are the most comprehensive approaches, since similar attention is given to the organizational, financial and technical perspectives. Nevertheless, more work needs to be done in order to facilitate their implementation, namely providing tools and techniques to organize and analyse the information of each implementation step and to support decision-making.

4. Conclusion

In this paper, a literature review about the implementation of CBM is presented. The main purpose was to identify and analyze existing approaches to support CBM implementation. Most of the literature reviews in the field of CBM limits the scope to diagnostics and prognostics methods, and optimization models. However, to ensure accurate and cost-effective decisions, the selection and application of CBM methods and models must be addressed within comprehensive implementation approach. Thus, appropriate procedures should be defined and adapted to the requirements of each appliance.

The literature review showed that only a small number of studies provide approaches for implementing CBM. Although some of the existing procedures include an extensive list of implementation steps, more guidelines and tools are required to facilitate the application and enhance the effectiveness of each step. Methods to evaluate the costs-effectiveness of the CBM process should also be established. Furthermore, the proposed approaches still need practical validation and refinement, which only can be reached based on their application in different scenarios.

In general, the implementation of CBM in companies relies on the experience of maintenance technicians and it is not performed in a systematic manner. This circumstance can originate ineffective and inefficient decisions or discourage the application of CBM in companies where little technical knowledge exists. Therefore, the development of a generic and comprehensive methodology which can support the implementation of CBM to different types of equipment is a relevant matter. The methodology can be complemented with existing methods, techniques and tools.

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References

[1] M. Schreiber, J. Klöber-Koch, C. Richter, G. Reinhart, Integrated Production and Maintenance Planning for Cyber-physical Production Systems, Procedia CIRP. 72 (2018) 934–939.

[2] J. Harte, Introduction, in: Maintenance, Replace. Reliab., Second, CRC Press Taylor & Francis Group, New York, 2013: pp. 1–25.

[3] L. Fedele, Methodologies and Techniques for Advanced Maintenance, First, Springer-Verlag London Limited, London, 2011.

[4] A.C. Márquez, The Maintenance Management Framework: Models and Methods for Complex Systems Maintenance, First, Springer-Verlag, London, 2007.

[5] A. Diez-Olivan, J. Del Ser, D. Galar, B. Sierra, Data fusion and machine learning for industrial prognosis: Trends and perspectives towards Industry 4.0, Inf. Fusion. 50 (2019) 92–111.

[6] R. Ahmad, S. Kamaruddin, An overview of time-based and condition-based maintenance in industrial application, Comput. Ind. Eng. 63 (2012) 135–149.

[7] B. Al-Najjar, On establishing cost-effective condition-based maintenance: Exemplified for vibration-based maintenance in case companies, J. Qual. Maint. Eng. 18 (2012) 401–416.

[8] A.K.S. Jardine, D. Lin, D. Banjevic, A review on machinery diagnostics and prognostics implementing condition-based maintenance, Mech. Syst. Signal Process. 20 (2006) 1483–1510.

[9] Y. Peng, M. Dong, M.J. Zuo, Current status of machine prognostics in condition-based maintenance: A review, Int. J. Adv. Manuf. Technol. 50 (2010) 297–313.

[10] J. Lee, F. Wu, W. Zhao, M. Ghaffari, L. Liao, D. Siegel, Prognostics and health management design for rotary machinery systems - Reviews, methodology and applications, Mech. Syst. Signal Process. 42 (2014) 314–334.

[11] K.L. Tsui, N. Chen, Q. Zhou, Y. Hai, W. Wang, Prognostics and Health Management: A Review on Data Driven Approaches, Math. Probl. Eng. Hindawi Publ. Corp. 2015 (2014).

[12] A.J.G. López, A. Crespo Márquez, J.F. Gómez Fernández, A. Guerrero Bolaños, Towards the Industrial Application of PHM: Challenges and Methodological Approach, in: Eur. Conf. PHM Soc. 2014 Proc., Nantes, France, 2014: pp. 1–10.

[13] A. Prajapati, J. Bechtel, S. Ganesan, Condition based maintenance: a survey, J. Qual. Maint. Eng. 18 (2012) 384–400.

[14] A.J. Guillén, A. Crespo, J.F. Gómez, M.D. Sanz, A framework for effective management of condition based maintenance programs in the context of industrial development of E-Maintenance strategies, Comput. Ind. 82 (2016) 170–185.

[15] G. Niu, B.S. Yang, M. Pecht, Development of an optimized condition-based maintenance system by data fusion and reliability-centered maintenance, Reliab. Eng. Syst. Saf. 95 (2010) 786–796.

[16] A. Rastegari, M. Bengtsson, Implementation of Condition Based Maintenance in manufacturing industry - A pilot case study, in: 2014 Int. Conf. Progn. Heal. Manag., IEEE, 2014: pp. 1–8.

[17] R.M. Ayo-Imoru, A.C. Cilliers, A survey of the state of condition-based maintenance (CBM) in the nuclear power industry, Ann. Nucl. Energy. 112 (2018) 177–188.

[18] R. Ahmad, S. Kamaruddin, A review of condition-based maintenance decision-making, Eur. J. Ind. Eng. 6 (2012) 519–541.

[19] A. Bousdekis, B. Magoutas, D. Apostolou, G. Mentzas, A proactive decision making framework for condition-based maintenance, Ind. Manag. Data Syst. 115 (2015) 1225–1250.

[20] B. Snider, Failure prevention — The ultimate asset management strategy, Hydrocarb. Process. (2016) 47–53.

[21] J.Z. Sikorska, M. Hodkiewicz, L. Ma, Prognostic modelling options for remaining useful life estimation by industry, Mech. Syst. Signal Process. 25 (2011) 1803–1836.

[22] H.B. Jun, D. Kim, A Bayesian network-based approach for fault analysis, Expert Syst. Appl. 81 (2017) 332–348.

[23] R. Jiang, A multivariate CBM model with a random and time-dependent failure threshold, Reliab. Eng. Syst. Saf. 119 (2013) 178–185.

[24] X.S. Si, W. Wang, C.H. Hu, D.H. Zhou, Remaining useful life estimation - A review on the statistical data driven approaches, Eur. J. Oper. Res. 213 (2011) 1–14.

[25] B. de Jonge, R. Teunter, T. Tinga, The influence of practical factors on the benefits of condition-based maintenance over time-based maintenance, Reliab. Eng. Syst. Saf. 158 (2017) 21–30.

[26] A.J. Guillén, A. Crespo, M. Macchi, J. Gómez, On the role of Prognostics and Health Management in advanced maintenance systems, Prod. Plan. Control. 27 (2016) 991–1004.

[27] Nam-Ho Kim, D. An, J.-H. Choi, Prognostics and Health Management of Engineering Systems: An Introduction, First, Springer Nature, Cham, 2017.

[28] A.V. Rocha, D.F. Melo, T.A.C. Maia, V.N. Ferreira, B.J.C. Filho, IoT-Based Degradation Management for Self-Healing Power Converters, 2019 IEEE Appl. Power Electron. Conf. Expo. (2019) 2802–2809.

[29] W. Elghazel, J. Bahi, C. Guyeux, M. Hakem, K. Medjaher, N. Zerhouni, Dependability of wireless sensor networks for industrial prognostics and health management, Comput. Ind. 68 (2015) 1–15.

[30] Departement of Defense, Condition Based Maintenance Plus DoD Guidebook, DoD, Washington D. C., 2008.

[31] J.-H. Shin, H.-B. Jun, On condition based maintenance policy, J. Comput. Des. Eng. 2 (2015) 119–127.

[32] S. Alaswad, Y. Xiang, A review on condition-based maintenance optimization models for stochastically deteriorating system, Reliab. Eng. Syst. Saf. 157 (2017) 54–63.

[33] H.J. Hwang, J.H. Lee, J.S. Hwang, H.B. Jun, A study of the development of a condition-based maintenance system for an LNG FPSO, Ocean Eng. 164 (2018) 604–615.

[34] ISO ISO 13374-1, Condition monitoring and diagnostics of machines — Data processing, communication and presentation — Part 1: General guidelines, International Standards Organization, Geneva, 2003.

[35] MIMOSA, Open Systems Architecture for Condition-based Maintenance (OSA-CBM), Machinery Information Management Open Standards Alliance (MIMOSA), 2006.

[36] Y. Lei, N. Li, L. Guo, N. Li, T. Yan, J. Lin, Machinery health prognostics: A systematic review from data acquisition to RUL prediction, Mech. Syst. Signal Process. 104 (2018) 799–834.

[37] A.H.C. Tsang, W.K. Yeung, A.K.S. Jardine, B.P.K. Leung, Data management for CBM optimization, J. Qual. Maint. Eng. 12 (2006) 37–51.

[38] V.H. Jaramillo, J.R. Ottewill, R. Dudek, D. Lepiarczyk, P. Pawlik, Condition monitoring of distributed systems using two-stage Bayesian inference data fusion, Mech. Syst. Signal Process. 87 (2017) 91–110.

[39] Y. Lin, X. Li, Y. Hu, Deep diagnostics and prognostics: An integrated hierarchical learning framework in PHM applications, Appl. Soft Comput. J. 72 (2018) 555–564.

[40] A.G. Starr, A structured approach to the selection of condition based maintenance, in: Fifth Int. Conf. Fact. 2000 - Technol. Exploit. Process, IEE, 1997: pp. 131–138.

[41] ISO 17359, Condition monitoring and diagnostics of machines - General guidelines, International Standards Organization, Geneva, 2018.

[42] United States Army, ADS-79D-HDBK - Aeronautical Design Standard Handbook for Condition Based Maintenance Systems for US Army Aircraf, 2013.