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PHM Applicability to BOP System Maintainability and Operations Management: A Systematic Literature Review

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Abstract The constant advancement of systems maintenance concepts has emerged a methodology focusing on the improvement of reliability, availability and operational safety named as Prognostic and Health Management (PHM). PHM encompasses failure prognoses of an equipment or system, providing an estimate of time until a failure occurs or the remaining useful life (RUL). The prognosis makes possible to predict an undesired event before it occurs, avoid catastrophic accidents, minimize overall maintenance costs and operations downtime in complex systems. Blowout Preventer (BOP) is considered a critical equipment in oil and gas industry as its downtime cost varies between US$ 1 million to US$ 1.2 million per day (Martins et al.,2018). In response to the emerging opportunities and in order to obtain updated concepts on the theme, the present research aims to conduct a Systematic Literature Review (SLR) on PHM applied to a BOP system through a quantitative and qualitative analysis of the literature, following the steps proposed by (Cooper, 2005). The research selected 69 articles to be analysed. The results expanded the knowledge on the subject as well as recent advances of PHM and demonstrated that the number of studies in this field are increasing and is a relevant methodology, when complemented with other techniques, for a better decision-making in maintainability and operations management.

Keywords: Maintainability and operations management; Prognostics Health Management (PHM); Blowout Preventer (BOP).

1 Introduction

In a globalized and competitive world, companies invest in processes and strategies to improve market prominence and growth (Fernandes e Santoro, 2005; Palomino e Carli, 2008). In this search, one of the strategies is the constant enhancement of production and operations management, which can be defined as: "project, management and control of processes that transform inputs into services and products, to both internal and external customers" (Krajewski, 2009). In this sense, from the point of view of production and operations management, there is an increase of effective strategies for equipment and production processes maintenance in order to guarantee product delivery on time, with quality and reliability, cost, adding value to the customer and the company (Pintelon e Gelders, 1992; Garg e Deshmukh, 2006). Thereby,

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maintenance of industrial manufacturing equipment can be defined as: “all activities necessary to restore equipment to, or keep it in, a specified operating condition” (Pintelon e Gelders, 1992).

Industries have been constantly facing paradigm changes, regarding design, monitoring and maintenance of dynamic and complex systems, especially in oil and gas chain (Mutlu et al., 2018). The need in obtaining better reliability and availability of systems and components led to advances in maintainability, diagnostic and prognostic techniques (Vachtsevanos et al., 2006). New methods, as Condition-Based Maintenance (CBM) and Prognostic and Health Management (PHM), started to be used to increase availability and to guide maintainability to operations management improvement. Through these methods, the estimated operation time of an equipment before failure can be determined, enabling actions for a better maintainability, helping industries to avoid production downtimes, unnecessary costs and disruptions in supply chain, affecting operations management (Ali et al., 2015). Thus, CBM and PHM are considered an approach capable to enhance maintainability practices significantly like operations management strategies, due to the interdisciplinarity between different areas (Vachtsevanos et al., 2006). CBM helps critical systems to function with greater reliability, security and availability, reducing operational costs (Sun et al., 2012).

RAM (Reliability, Availability, Maintainability) trinomial is considered one of the most important functional requirements sets in operations systems (Zou et al., 2016). In oil and gas operations’ chain, maintenance activities need to be carried out at the most appropriate time in order to increase predictability and operations management capacity, as equipment failures paralyze operations, causing downtime, process’ disruptions and increased costs - a downtime cost varies between US$ 1 million to US$ 1.2 million per day (Martins et al.,2018). Among the equipment that most impact the costs during drilling or completion operations is the Blowout Preventer (BOP) (Huse e Alme, 2013). It can be considered as a set of valves that are remotely controlled from the rig and act as a second security barrier in the well control, during the drilling and completion of oil and gas production wells, allowing the well to shut if there is a unbalanced difference between the pressure of the mud column and the well pressure. In some cases, it is necessary shears the drilling column and seals the well, in order to ensure the integrity of the equipment (Martins et al., 2018; Mutlu et al., 2018).

As a result of the costs caused from downtime processes due to maintainability problems, organizations are concerned about reliability and availability of critical systems and components, such as BOP, in the oil and gas industry (Vachtsevanos et al., 2006). In this sense, the authors of this article are conducting a research project in the Oil and Gas Exploration and Production industry (E&P), to reduce downtime in industries related through the application of CBM and PHM in the BOP system. However, article (Martins et al.,2018) takes priority over the CBM methodology, not delving into concepts and applications of PHM, preferably in the oil E&P industry that can be applied to the BOP system to guide maintainability strategies aligned to operations management optimization. (Si et al., 2013) argue that PHM is an efficient tool with a systematic approach to assess a system reliability and its real operating conditions, predicting failures and mitigating operational risks. In PHM, prognoses can lead to a better reliability of the system, helping decision-making in preventing systems disruptions, improving maintainability and operations management.

Thus, the authors of this paper argue that the improvement of knowledge in PHM applications is relevant to diagnose gaps in maintainability knowledge pertinent to operations management improvement in oil and gas industries. RSL can be seen as a tool that helps researches to identify gaps in the theory as well central issues for future researches (Conforto et al., 2011). Besides that, RSL can be seen as a consistent methodology to be used when researches seek to fulfil scientifical and academical hiatus, increase understanding and knowledge on a subject and to structure studies of scientific productions on a given theme (Cooper, 2005).

Hence, the objective of this paper is to conduct a Systematic Literature Review (SLR) aiming to identify PHM applications specifically in BOP systems. Thus, it allows the identification of conditions for monitoring the components of this equipment and its interpretation of the characteristics of operation and influence on the occurrence of failures. In addition to bringing to light recent studies and advances in the PHM application and thus assisting companies in the oil and gas sector that operate with BOP to improve their maintenance management.

2 Methodology

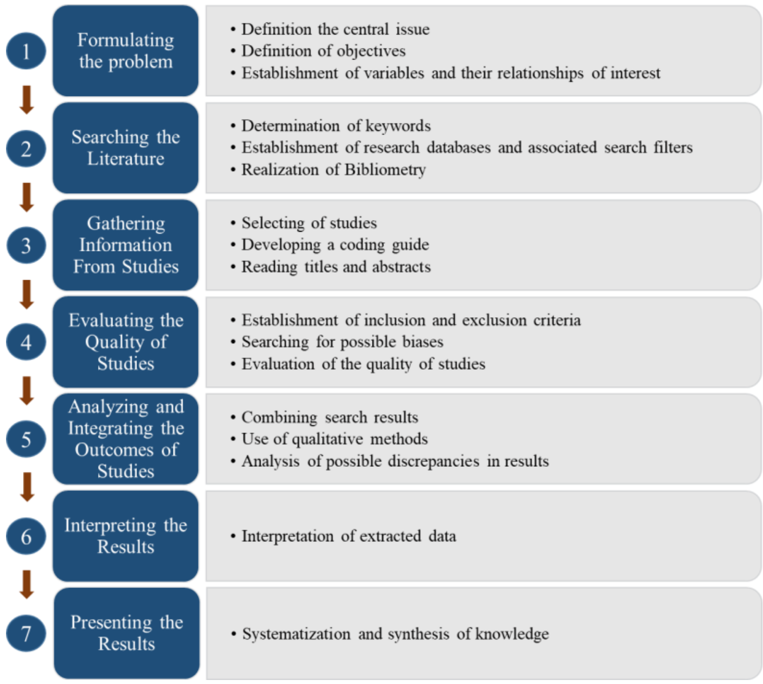

Fig. 1 SLR Flowchart elaborated to this research

SLR is a methodology that attempts to relevant theories, critically analyses the research, tries to resolve conflicts in the literature and identify central issues for future researches. The results allow to identify gaps in the theory that can be explored by other researchers that were not identified in similar studies due to superficiality and lack of rigor in bibliographical review (Cooper, 2005; Conforto et al., 2011). (Mulrow, 1994) stated that the use of systematic procedures increases reliability and precision of the study conclusions and results. Through SLR is possible to structure studies of scientific productions on a given theme, in referenced databases in a specific space of time (Miranda, 2018). (Galvão e Pereira, 2014) argued that one of the main characteristics of this type of review is the data collection coverage and the use of research criteria, in order to allow its replication. According to (Thomé et al., 2016): "SLR uses a well-defined and rigorous criteria to identify, appraise and synthesise the literature, including a list of studies published in peer-reviewed and gray literature", stipulating a critical assessment of the available literature on a specific subject. To elaborate this SLR, the 7 steps proposed by (Cooper, 2005) were used as reference, where each step comprises specific tasks according to the context of this research, detailed in Fig. 1.

In Step 1, the research central issue was defined as: PHM applied to BOP, and then, the general and specific objectives were designated, as well as the delimitation and definition of study variable(s). In Step 2, a literature search was performed, through the identification of keywords that were the objective of the research. Electronic databases were also selected: Scopus and Onepetro, where filters helped to choose the most relevant studies defined through analysis. It is worth mentioning that a bibliometric analysis was carried out in order to provide subsidies for this step elaboration (Borner et al., 2007). In Step 3, after defining the documents to be examined, the most relevant information was extracted through titles and abstracts previous reading and later evaluation of their quality. In Step 4, inclusion and exclusion criteria were established in order to identify their relevance, assessing the existence of possible biases, as well as duplications and quality of publications. Documents that met the inclusion and exclusion criteria were fully read, in Step 5, to be synthesized through theoretical discussions about the central research question. The results obtained in the literature synthesis were interpreted in Step 6. Thus, from the study evaluation, conclusions were presented regarding the extracted data and documents. In Step 7, results and general conclusions of the study were presented based on the documents' syntheses, interpretations and inferences.

2.1 Details of the Method Applied

The research's scope was defined in Step 1. Table 1 shows the keywords used, the total of publications found in every search and the number of selected publications (69) that composed the final sample. A bibliometric study was carried out (Step 2). The terms were searched together (with the use of quotation marks) and individualized mentions were disregarded. In this way, original term full writing was utilised. The Scopus database was used, as it encompasses a large volume of abstracts and citations from different areas, enabling bibliometric analyses support. Also, OnePetro database was employed because it allows access to Oil and Gas Exploration and Production (E&P) Industry technical papers. The search was carried out between October 25 and November 1, 2018, using advanced search according to each database.

Table 1 Selected documents number

Keywords	Base	Total of publications found	Total of publications selected
("Prognostic and health management")	Scopus	1,515	30
("Prognostic and health management") AND ("Blowout Preventer" OR "BOP")	Scopus e Onepetro	1	1
(("Reliability" AND ("Blowout Preventer" OR "Blowout Preventers" OR "BOP"))	Onepetro	1,739	24
("Prognostic and health management" OR "Blowout Preventer")	Scopus	2,245	4
("Prognostic and health management" AND "Condition based Maintenance")	Scopus	160	10
Total	-	5,660	69

The first search ("Prognostic and Health Management") at Scopus resulted in 1,515 publications. Engineering (42.5%) and Computer Science (22.5%) are the prominence fields. It was found that 66% of the documents were published between the years 2013 to 2018. The second search was carried out in both databases (Scopus and Onepetro) including BOP (("Prognostic and health management") AND ("Blowout Preventer" OR "BOP")). The "AND" connective was used to obtain publications with the two keywords at the same time. Only 1 result was obtained in Onepetro database. In the third search, Onepetro (("reliability" AND ("Blowout Preventer" OR "Blowout Preventers" OR "BOP")), a total of 1,739 publications were found. The fourth search, at Scopus with the use of "OR" connector ("Prognostic and health management" OR "Blowout Preventer"), resulted in 2,245 publications corresponding to different thematic areas since the year 1968 and Engineering (40.5%) and Computer Science (17.0%) eminence is also perceived. The fifth search aimed to find concepts and possible relationships between CBM and PHM ("Prognostic and health management" AND "Condition based Maintenance"). This analysis resulted in 160 publications in different thematic areas since 2001. Also, most of publications was found in Engineering (44.7%) and Computer Science (21.4%).

In order to certify that all documents of interest were selected a coding guide (questions) was developed (Step 3), as: 1) Does the document contain theoretical definitions about PHM?; 2) Do these publications contemplate the advantages and disadvantages of applying PHM?; 3) Are there documents with PHM applications in specific components?; 4) Are there documents that address the main variables of interest related to PHM?; 5) Are there documents containing definitions and main characteristics of the BOP's operation?; 6) Do the selected publications include conditions monitoring approaches for BOP or any of its systems? In this study, all the questions in the coding guide were satisfied, thus it can be earned that all documents of interest were selected (Cooper, 2005).

The inclusion and exclusion criteria were established (Step 4). For Scopus, the first filter was applied, restricting the search to Engineering, Computer Science and Mathematics fields. Also, documents from 2013 to 2018 were selected (years with the largest number of publications), resulting in 941 documents. The third criterion was regarding the number of citations – documents with 50 or more citations were selected. Finally, after duplicity analysis with documents found in the other searches, sample was reduced to 30 documents. It should be noted that in the second search, only 1 document was found. For the third search (OnePetro), the initial criterion was also the year of publication and it was limited to Conference Articles. After the analysis of duplicity, the amount was reduced to 24 documents. In the fourth search (Scopus), after applying filters and selection criteria, the number of publications was reduced to 1,804. The 50 most cited in descending order were pre-selected, predominantly articles (96%). An analysis of the titles was carried out among the publications pre-selected in the first search. After duplicity analysis, only 4 documents were selected.

Next, filters and selection criteria were applied to the documents from the fifth search (Scopus) - the number of publications was reduced to 146. After duplicity analysis, the sample was reduced to 10 publications. The total number of selected publications for full reading and analysis were 69. In order to add more subsidies to the selected articles, national and international standards related to PHM approach were included in the study, such as: ISO 13372, ISO 13374, ISO 17359, ISO 14224 and NBR 5462 (Step 5). As a result of SLR research, the following sections present the results on PHM, the use of PHM to BOP, as well as the advantages and disadvantages of PHM, according to steps 6 and 7 of the proposed method.

3 Results

3.1 Details of the Method Applied

To synthesize the studies about PHM and consequently evaluate their divergences and convergences, Table 2 presents some definitions of PHM summarized. It can be observed that the concepts converge according to PHM relationship with operations reliability improvement, given to its proactivity. Although all the authors define PHM as an approach that makes it possible to estimate the remaining useful life (RUL), using information obtained in real-time monitoring as an input, some authors differ in the type of classification, considering as a process, discipline, methodology or a set of tools and techniques. In this sense, it is concluded that PHM can be defined as a process, discipline or methodology capable of detecting and predicting failures in real-time, providing a prognosis to the equipment or component RUL supporting decision-making when maintenance should be carried out. Thus, increasing equipment availability and reducing costs from interventions and downtimes, improving maintainability and operations management.

Table 2 PHM summarized definitions

Definition
Set of activities based on data monitoring and processing to provide a diagnostic and prognostic. It helps in decision making regarding maintenance actions in preserving a system through the gathered information (Jouin et al., 2016).
PHM methodology has been proposed focusing on detection, prediction and management of complex engineered systems (Liao e Pavel, 2016).
It is a process of detecting abnormal conditions by diagnosis and prognostics (Ali et al., 2015).
It is an emerging engineering discipline which links studies of failure mechanisms and life cycle management, extending operations life reducing costs (Javed et al., 2015).
PHM is an enabling discipline consisting of technologies and methods to assess the reliability of a system, to determine the advent of failure, and to mitigate system risk (Si., 2015).
It is a framework that offers a complete set of tools for managing system health with individualized solutions (Tsui et al., 2015).
Aims to determine the advent of systems failure to mitigate system risk through the evaluation of system reliability in terms of the current life-cycle conditions (Li e Xu, 2015).
It is an emerging science consisting of tools and techniques to evaluate reliability of a component or system to mitigate system risk (Rezvanizaniani et al., 2014).

Table 2 PHM summarized definitions (continued)

One key enabler to improve system safety, increase system operations reliability and availability, decreasing unnecessary maintenance and reducing systems costs (Tang et al., 2014).
As an engineering discipline PHM aims to provide an integrated view of an overall system health state. When employing such system, the health of a machine, component or system can be known at any time, and eventual disruption can be predicted and avoided (Lee et al., 2014).
The method allows reliability assessment of a system under actual application conditions, and its purpose is to maximize the system's operational availability and safety (Xu et al., 2014).
It is a predictive tool aiming to reduce uncertainties' impacts and give users the opportunity to proactively implement solutions to prevent system's performance loss (Lee et al., 2013).
Responsible for monitoring the system integrity, diagnosing failures in real time, evaluating the remaining useful life of the equipment, making possible to support maintainability (Du et al., 2013).

The identified definitions show the potential of the methodology PHM when seeking to manage the reliability and availability of systems, guided by the real-time monitoring of operating conditions and their influence on failure mechanisms and life cycle management to improve maintenance decisions. PHM conduction strategies include modules for incipient failure detection, condition assessment (diagnostic) and prediction of failure progression (prognostic). Thus, allowing for improvement in fault isolation, maintenance planning, and the reduction or elimination of inspections based on time.

3.2 PHM Prognoses

According to (Saxena et al., 2008), prognoses are emerging at CBM forefront for critical systems where came up the term PHM. Failure prognosis comprises the predictive part of a PHM system, providing an estimate of time until a failure event or RUL prediction (Si et al., 2011). Prognosis provides, over a sufficient period of time, end-user's needs satisfaction (Vachtsevanos et al., 2006). (Si et al., 2011) stated that PHM prognoses can generate an early warning of imminent failures in a system helping to make decisions for maintenance and execution of preventive actions. (Javed et al., 2015) consider the prognosis as an important process with future capabilities. It is based on the use of condition monitoring data from operational machines (acoustic signal, strength, vibration, temperature, etc.) to obtain useful resources, assess degradation level and predict failures evolution to assist maintainability.

(Heng et al., 2009; Sun et al., 2012; Tang et al., 2014; Ji et al., 2015) argued that most prognostic models can be divided into two main categories: Physics-Based models and Data-Based models. For (Peng et al.,2010; Galar et al., 2015) there are additional models such as: knowledge-based models and hybrid models. Physics-Based models or Model Based Approaches involve the development of mathematical models with more comprehensive techniques in order to describe the system physics and its failure mode. They use specific knowledge of systems mechanics, defects growth formulas and CBM data, providing a prognosis with a better knowledge accuracy. Data-Based methods strive to derive models directly from collected historical or performance data. They use statistical methods or artificial intelligence tools (neural networks and fuzzy logic) (Sun et al., 2012).

Thus, it is clear that the application of PHM must be preceded by a detailed study of the failure mechanisms for the construction of Physics-Bases Models, in order to describe the system's physics and its failure mode, and historical failure data or performance data that allow it to evolve in Data-Based Models and thus develop the model that best describes the degradation behaviour equipment.

3.3 Advantages and Disadvantages of Applying PHM

An effective PHM system is expected to provide early detection and isolation of component failure precursor, as well as to equip with means monitoring and predicting failure progression and support maintainability decisions. Data high complexity and dynamics are the challenges for current PHM techniques (Lee et al., 2014). Table 3 describes some advantages and disadvantages for using PHM. The great advantage is that PHM is a methodology that increases systems reliability, improving maintainability. Failure prognosis and consequently the strategic decisions of maintainability optimizes operations management, mainly related to downtime and costs reduction as operational systems availability rises (Lee et al., 2014; Liao e Pavel, 2016).

Table 3 Advantages and Disadvantages of applying PHM

Advantages	Disadvantages
Proactive maintenance, with increased equipment availability (Lee et al., 2014).	Unknown its potential in dynamic and complex systems (Lee et al., 2014).
Fault detection and isolation, before it occurs (Lee et al., 2014).	An understanding of all the aging mechanisms that occur in the equipment is necessary (Jouin et al., 2016).
Autonomous activation of the maintenance schedule (Lee et al., 2014).	Difficulty in extracting correct data that correlates with the progression of the failure (Ramasso et al., 2013; Liao e Pavel, 2016).
Helps to preserve the system, extending its useful life (Jouin et al., 2016).	Supposes that systems are subject to stochastic deterioration (Tsui et al., 2015).
Improves reliability and maximizes satisfactory level throughout the equipment's life cycle (Liao e Pavel, 2016).	High initial cost (Tsui et al., 2015).

Among the advantages, it stands out that the increased availability, reliability and integrity of the equipment throughout its useful life, generated by the proactive maintenance, through the fault detection and isolation before these occur. In addition to allowing a maintenance schedule with autonomous activation. The disadvantages, on the other hand, show the need for a deep understanding of the dynamics and complexity of the system under analysis, given the difficulty of understanding the failure mechanisms and obtaining historical data and monitoring in real time.

3.4 PHM Applicability in BOP

PHM can be applied to different equipment, as most studies refer to batteries and bearings, where frequent monitoring parameters are vibration and temperature, as they have more historical data from different types of industry (Lee et al., 2014; Wang et al., 2016). The Table 4 exposes some of the PHM applications in the BOP equipment, showing which system of the equipment this approach is applied to, the objective of the study, the method or model used and the contributions to the literature.

Table 4 PHM applications to BOP

Application	Objective	Methods	Contribution
BOP dashboard	Failure diagnostics	New communication system	Assess possible integrity failures quickly and simply (Mckay et al., 2012).
BOP internal components	Knowledge of events, such as degradation, from sensors installation	Integration of risk-based integrity management software	Monitoring of critical functions (Turner e Loustau, 2015).
Risers	Virtual sensors to provide an innovative solution for component monitoring	Data-Based models	Predictive inspection planning (Sundararaman et al., 2018).
Pressure regulator	Monitor the performance and health of a BOP pressure regulator	Physics-based models	Method to differentiate regulator leakages within the same BOP (Mutlu et al., 2018)

Table 4 PHM applications to BOP (continued)

Application	Objective	Methods	Contribution
BOP operations	Monitor the reliability of BOPs during operation	Risk and reliability model	Compares current state data during operations to the ones required by regulatory standards (Huse e Alme, 2013).
BOP operations	Real-time risk analysis of drilling operations using different drilling techniques	Models based on Bow-Tie analysis	Effective operations management, downtime minimization and accidents avoided (Abimbola et al., 2014).
BOP operations	Improve BOP's reliability, availability and operational security	Program developed by a drilling contractor	Downtime reduction in operation (Martins et al., 2015).
BOP operations	Root cause failure diagnostic and real-time reliability assessment	Bayesian networks and dynamic Bayesian networks	Reliability study of multilevel and redundant systems (Cai et al., 2013; Cai et al., 2015).
BOP operations	Viable performance based on reliability and maintainability requirements	Reliability model	Knowledge of the mean time between maintenance, availability system, and assisting proactive maintenance decision (Zou et al., 2016).
BOP control system	Diagnostic and prognostic of a well system failure	Bayesian networks	Improvement of the operation safeness (Cai et al., 2015).
BOP control system	Test and optimize solutions to resolve performance failures	Mathematical model	Performance and reliability in a drilling control system (Barker et al., 2016).
BOP control system	Availability of BOP in operation, in order to reduce downtime	Reliability analysis	Standardization of operational decision-making process (Mutlu et al., 2017).
BOP control system	Detect and monitor control leakage fluid within the BOP hydraulic control system	Physics-Based models	Performance measurement for further analysis of the severity (Wassar et al., 2018).
BOP control system	Critical information on the availability of the systems used for the well closure operation	Calculation of the mean probability of failure on demand	Assists in critical security measures and in improving the operational performance of the system (Zulqarnain et al., 2018).

Table 4 presents that the studies of reliability and PHM in specific components of the BOP are still few, but growing, mainly after the Deepwater Horizon accident in 2010. Most of publications are focused on BOP control system management and on its operability, they are recent and still initial applications, focused on the understanding of failures and the identification or preliminary data analysis. However, there is an understanding of the importance of this subject for the improvement of operations in the oil and gas industry, concerned to its safeness, equipment availability improvement, operating costs reduction and maintainability enhancement (Sattler et al., 2013; Martins et al., 2015).

4 Conclusions

This research proposed to study the methodology PHM applied to BOP system through a SLR, bringing to light recent studies and advances in PHM application in the oil and gas industry concerned to maintainability and operations management improvement. A SLR was conducted in order to analyse possible opportunities and gaps. The central issue and objectives were defined as well as the variables and electronic bases. In order to be able to synthesize data obtained, most relevant information was extracted from the documents, by prior reading of titles and abstracts and through application of inclusion and exclusion criteria, which made it possible to assess the documents relevance and quality. It was possible to interpret and theoretically synthesize the selected documents, presenting consistent results and conclusions as preconized by RSL (Cooper, 2005; Thomé et al., 2016).

The research sample was composed of 69 articles selected for full reading added with national and international standards related to PHM. In this sense, this research filled some academical gaps presenting PHM advantages and disadvantages, industrial applications, BOP systems studies and maintainability and operations management improvement through a better decision-making process through data and knowledge from PHM. PHM involves several areas at different stages of data and technological development, however, for the purposes of this study, PHM was focused within maintainability and its applicability to BOP, involving the detailed study of the components of that system and the identification of physics of failure models.

The systematic literature review showed the importance of the existence of data for the use of PHM, due to the fact that few studies are related to BOP real-time monitoring for data acquisition (primordial condition to PHM) and reliability techniques are usually used for failure diagnosis. This is due to the fact that the BOP is composed by several components and integrated systems, making it a complex system, designed in different styles, sizes and pressure ratings. Thus, one of the reasons for the difficulty of implementing PHM is related to the sensing for multicomponent equipment, which is initially expensive and complex to implement.

Thus, the study demonstrated that although some prognostic methods have been proposed for different applications, the progress to make an effective and efficient approach is still limited. Usually, the lack of assessment of the complex and non-linear behaviour of machines subject to degradation in a dynamic operating environment prevents professionals from developing accurate models for prognoses. In general, the difficulties found in the analysed documents permeate the idea that PHM is a new and little-know science. However, it is believed the tendency for these disadvantages to decrease, since with greater use of this methodology and the advancement of sensing technologies, the costs and complexities in the implementation will be lower. It is perceived that this study can contribute to companies that work with BOP showing the current maintenance scenario and future trends, such as self-maintenance techniques, as it is an attractive and new area for future research.

PHM is considered the basis, when complemented with other techniques, for a better BOP maintenance, maintainability and operations reliability increase (Si et al., 2013; Lee et al., 2014; Javed et al., 2015; Tsui et al., 2015). It showed to be a prominent methodology applied in many industries focusing to improve equipment, systems and operations reliability and availability through failure and downtime reduction (Tsui et al., 2015). Real-Time monitoring, failure diagnosis and prognosis in complex systems linked with data science techniques seek to provide better understanding of the whole system and knowledge for the decision-making process to improve operations management through maintainability. This research can contribute to companies in oil and gas industry that use BOP systems showing the current panorama of reliability and availability in the industry and future trends for better maintainability and operations management. For future research, a deepen study of other maintenance techniques combined with PHM is recommended for the improvement of maintainability, as well as expand the study to other types of industries.

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