Quantifying the Added Value of Adopting Condition Monitoring to Subsea Blowout Preventer (BOP)

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As the technology for fault detection, diagnosis and prognosis has become increasingly affordable over time, offshore oil and gas industries have adopted condition-based maintenance (CBM) over corrective and time-based maintenance as their preeminent maintenance regime for safety instrumented assets. This has made determining the economic added value of CBM strategy very crucial for organizations. This paper presents a framework to perform an economic feasibility analysis of implementing CBM in subsea oil and gas production systems, with a particular focus on blowout preventers (BOPs). Though the BOP is one of the most important safety-critical drilling equipment in the oil and gas sector, to the best of our knowledge there is no study examining the economic added value of CBM strategy. Our methodology takes into account both the costs associated with CBM implementation (including acquisition, installation, and operation and maintenance (O&M) costs) as well as the benefits which are accrued from implementing CBM (such as increased revenue and reduced repair costs). An accurate and robust cost-benefit analysis (CBA) is performed for the adoption of CBM in BOPs and some metrics such as net present value (NPV) and cost-benefit ratio (CBR) are calculated. The proposed approach in this study will provide asset managers and maintenance professionals with a key decision-making tool with which to make an informed financial case for implementing CBM.

Keywords: Condition monitoring, Blowout preventer (BOP), diagnosis, prognosis, asset management, cost-benefit analysis, subsea oil and gas.

1 Introduction

Due to the perpetually increasing demand for energy in today's world, oil and gas companies are having to deal with increasing capital and operational expenses. This is seen to be as a result of a combination of factors such as increasing dearth of conventional energy sources, the need to increase extraction/production of already-mature sources, as well as the challenges associated with the recovery of reserves situated in highly remote locations (further offshore and deeper underwater) (Rahim *et al.*, 2010). This, along with the availability of affordable new technologies which help operators diagnose and troubleshoot potential failures, has spurred the push towards the application of condition-based maintenance (CBM) as the pre-eminent maintenance regime for safety instrumented systems in the oil and gas industry (Elusakin *et al.*, 2019).

CBM is a subset of preventive maintenance (PM) that considers the repair or replacement decision based on the normal and abnormal condition of equipment. In this strategy, maintenance actions are performed only when the asset condition reaches a defined critical level (Mutlu *et al.*, 2018). According to Gugaliya and Naikan, (2019), though time-based maintenance has a comparatively lower initial investment requirement compared to CBM, it incurs considerably higher operating cost which makes it less cost-effective. Benefits of CBM to offshore oil and gas industry include the enhanced asset availability, reduction in maintenance task costs, increased equipment running time and enhanced safety assurance.

As a result of the increase in demand for energy, the importance of subsea blowout preventers (BOPs) as a vital safety instrumented system cannot be overstated (Shafiee *et al.*, 2020). This is made all the more evident by the growing existence of improved environmental protection and safety policies. The BOP is deemed to be the last safety barrier against erratic well pressures which can eventually lead to a blowout (Sattler 2013). It also serves to confine well fluids to the well bore, provide an avenue through which fluid can be added and taken out of the wellbore, and seal the wellhead if needed. The subsea BOP is made up of one or multiple annular preventers,

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three to six ram preventers, two hydraulic connectors (wellhead and lower marine riser package connector), a control system, and multiple choke and kill valves (Elusakin and Shafiee, 2020). The configurations of a conventional and a modern BOP are shown in Figure 1.

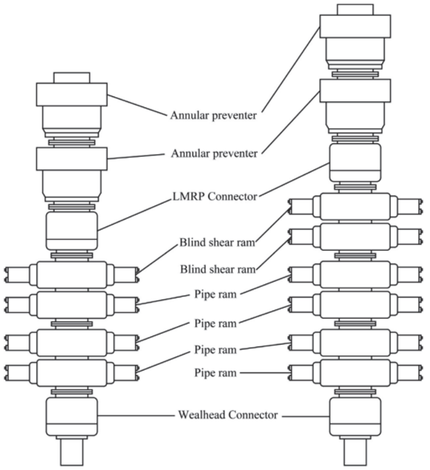

Figure 1 The configurations of a conventional (left) and a modern (right) BOP (Liu *et al.*, 2015)

According to Shafiee (2015), maintenance is more of an economic problem with a reliability component rather than vice versa, hence the need to perform an accurate and robust cost-benefit analysis (CBA) to determine the financial viability of a particular maintenance strategy. The decision to invest in adopting CBM is not always dependent on profitability alone. Where money allocated towards investment is limited, funds might be put to better use on an alternative endeavour even if the benefit-cost indicator shows a positive result.

A number of studies on the technical considerations of implementing CBM in subsea BOPs have been performed (see e.g. Carter *et al.*, 2014; Turner and Loustau, 2015; Xiu *et al.*, 2015). However, though analysis of the financial justification of CBM implementation is just as important, there remains an obvious lack of research committed to addressing this gap. This study therefore presents a framework to perform a CBA regarding the adoption of CBM in subsea BOPs. To the best of the authors' knowledge, this is the first study that applies CBA methods to determine the economic added value of adopting CBM in subsea oil and gas production systems. Our analysis takes into account both the costs associated with CBM implementation (including acquisition, installation, and operation and maintenance (O&M) costs) as well as the benefits which are accrued from implementing CBM over the lifetime of the subsea BOP (such as increased revenue and reduced repair costs). The proposed methodology is validated with the adoption of a real condition monitoring system (CMS) in a modern subsea BOP system.

The rest of this paper is organised as follows. Section 2 provides a background to this research and discusses the existing literature on CBA and its application to feasibility analysis of CBM. In section 3, the CBA framework is presented and it is applied to a case study. Lastly, section 4 concludes the study and suggests options for future works.

2 Research Background

2.1 Cost-Benefit Analysis

The primary purpose of a CBA is to determine if a proposed action or endeavour is financially viable/profitable (Børresen 2011). It is a tool for analysing investments/projects to determine if they are financially viable. In the case where there are limited resources, CBA is a tool to determine which projects should be chosen (Mishan and Quah, 2007). The process for CBA involves determining investment alternatives and base case, determination of costs and benefits, selection of required financial parameters, data collection, calculation of the present value of benefits and costs, application of chosen CBM technique and finally, acceptance or rejection of an investment alternative (Animah *et al.*, 2018). According to Kull *et al.* (2013), one major benefit of a CBA is its clear and thorough analysis of profit and loss, making investment decisions more transparent. Another benefit of CBA is the compatibility of its result to actual market tools (Shafiee *et al.*, 2019). Different CBA techniques include benefit cost ratio (BCR), internal rate of return (IRR), net present value (NPV) and payback period. In what follows, these techniques are briefly explained:

2.1.1 Net Present Value

The NPV of an investment option can be determined by deducting the present value of the cash invested from the present value of the net cash receipt. A positive NPV value signifies a positive return on investment and vice versa (British Standard Institute, 2001). This is often considered the most preferred criteria for decision-making on a proposed investment. NPV can be calculated as (Gugaliya and Naikan, 2019):

$$NPV = \sum_{t=1}^{T} \frac{C_t}{(1+i)^t} - C_0 \tag{1}$$

where i is the required rate of return per year.

2.1.2 Internal rate of return

According to British Standard Institute (BSI) (2001), IRR is defined as the discount rate at which the net present value is equal to zero (NPV = 0). The IRR is calculated using the following equation:

$$0 = NPV = \sum_{t=1}^{T} \frac{C_t}{(1+IRR)^t} - C_0 \tag{2}$$

where C_t represents the net cash inflow after year t; T represents the project duration in years; C_0 is the initial investment expense and t represents the number of time periods. If the IRR of a proposed investment option is higher than the minimum internal rate of return (MIRR), this signifies that it will provide a higher return on investment than the required minimum.

2.1.3 Benefit Cost Ratio

BCR is the ratio of the present value of benefits to the present value of investment costs. An investment option is only considered financially worthwhile if the BCR is greater than 1. If there are multiple investment options and only one can be selected, then the option with the highest BCR is selected (Animah *et al.*, 2018). The BCR can be calculated using the following equation:

$$BCR = \frac{PVB}{PVC} = \frac{\sum_{t=1}^{T} \frac{B_t}{(1+i)^t}}{\sum_{t=1}^{T} \frac{C_t}{(1+i)^t}} \tag{3}$$

where PVB is the present value of benefits; PVC is the present value of expenses, i signifies the rate of return per year, C_t signifies costs in year *t* and B_t signifies the benefits in year *t*.

2.1.4 Payback Period

This can be defined as the period of time in which a particular undertaking is expected to recoup its initial investment. This is a quick and easy way to determine the profitability of an investment option. Payback period can be calculated using the following equation:

$$PP = \frac{C_0}{Yearly\ NCI} \tag{4}$$

where PP represents payback period and NCI represents net cash inflow. This method however, ignores the net cash flow after the payback period has elapsed (Belyadi *et al.*, 2016).

2.2 Cost-Benefit Analysis in CBM

The offshore energy industry, in the aftermath of the Macondo incident, has found itself under more pressure to move from the standard time-based maintenance to implementing CBM (Turner and Loustau, 2015). As this is still in its infancy, however, studies on CBM implementation which focus primarily on offshore oil and gas systems are few and far between. According to Thurston (2001), a CBM component contains seven modules: data acquisition, (sensors), signal processing, condition monitoring, health assessment (diagnosis), prognosis, decision support and presentation. These modules all factor into cost determination for CBA. The performance of a CBA is one of the prerequisites for implementing any form of CBM strategy (Amin 2016). This is backed up by ISO 17359:2018 (British Standards Institute 2018) in which the very first step to perform in CBM implementation is the CBA.

There are a number of studies which have investigated the economic costs and benefits of implementing CBM and condition monitoring systems in various industries. Pertinent research on cost-benefit analysis of CBM can be seen to go back as early as (Rajan and Roylance, 2000), in which a mathematical model was developed and proposed to predict the cost effectiveness of different maintenance programmes for batch process equipment in the pharmaceutical industry, with a particular focus on the economic analysis of practicing CBM. In Hess *et al.*, (2001), both the costs and benefits of different CBM technologies were analysed in order to make a decision as to the most effective technology. Rastegari and Bengtsson (2015) investigated how the cost effectiveness of employing CBM in the manufacturing industry can be analysed in order to avoid poor applications; while in the nuclear energy industry, IAEA (2007) examined the implementation strategies for CBM in nuclear power plants.

The offshore environment provides its own particular set of challenges which make implementation of CBM more difficult than in other industries. As a result of this, accurate determination of the costs and benefits of implementing CBM as a maintenance strategy is of immense importance. In Børresen, (2011), an offshore oil and gas separator was used as a case study for the implementation of CBM in conjunction with Integrated Operations (IO). A cost-benefit analysis, which took both reliability and financial perspectives into account, was performed on the implementation of the CBM programme in order to justify its use.

3 Cost-benefit analysis model

3.1 Costs of implementing CBM

It is absolutely paramount that all estimates on the costs of implementing CBM be as accurate as possible. CBM costs can be single, one-time expenses such as initial acquisition and installation costs as well as regular expenses such as those made for operation and maintenance (O&M) (Børresen 2011). The cost elements for implementing CBM are defined below:

3.1.1 Acquisition of CMS

The implementation of a CBM system requires a range of hardware and software components which may be purpose-built for the system in question or off-the-shelf components (Lebold *et al.,* 2002). Hardware components acquired for CBM implementation include sensors attached to the equipment offshore to monitor the condition of the system and data processing stations which can be on the same network as the sensors (rig-based) or located onshore. Due to the multi-component nature of the offshore drilling systems, different types of sensors need to be acquired to measure a host of parameters such as vibration, temperature and noise (Elusakin *et al.,* 2019). Health management software used for detailed analysis of the data collected using techniques such as overall trending and pattern matching will also have an initial acquisition fee. Both hardware and software must meet operational needs and must be able to seamlessly integrate into the overall maintenance structure (Gillespie 2015). The cost of acquisition of CBM components given by the equation:

$$C_{aq}^{Total} = C_{aq}^{H} + C_{aq}^{S} + C_{aq}^{T} \quad (5)$$

where C_{aq}^{H} is the cost of hardware acquisition, C_{aq}^{S} is the cost of software acquisition, and C_{aq}^{T} is the cost of training acquisition.

Acquisition of CBM hardware involves sensor, signal processor and server acquisition. Therefore,

$$C_{aq}^{H} = \ (N_{sensor} \times C_{sensor}) + \big(N_{sig.proc} \times C_{sig.proc}\big) + (N_{servers} \times C_{servers})\ , \quad (6)$$

$$C_{aq}^{S} = \ C_{license/yr} \times \ t_{licensing} \quad (7)$$

$$C_{aq}^{T} = N_{Training\ hours} \times C_{\frac{training}{hour}} \quad (8)$$

where N_{sensor} represents the number of sensors, $N_{sig.proc}$ represents the number of signal processors, $N_{servers}$ represents the number of servers, $N_{Training\ hours}$ represents the number of training hours, C_{sensor} represents the cost of sensors, $C_{sig.proc}$ represents the cost of signal processors, $C_{license/yr}$ represents the cost per year of licensing software, $t_{licensing}$ represents the duration of the software license in years and $C_{\frac{training}{hour}}$ represents the cost of training per hour.

3.1.2 Installation of CMS

Both the hardware and software used for CBM require installation. Installation cost includes labour costs, fees paid for tailoring the components to the specific system that requires the CBM and the cost associated with downtime. Downtime costs in this case will depend on how intrusive the installation of the monitoring equipment is, making it of paramount importance that installation be carried out in the design phase or when there is an optimal opportunity (Børresen 2011; Gillespie 2015). Cost of installing CBM components can be given by the following equation:

$$C_{inst} = C_{inst}^{labour} + C_{inst}^{logistics} + C_{inst}^{downtime} \quad (9)$$

where C_{inst} is the cost of installation; C_{inst}^{labour} is the cost of hiring labour for hardware/software installation; $C_{inst}^{logistics}$ is the cost of logistics involved in hardware/software installation; $C_{inst}^{downtime}$ represents the cost of downtime due to installation.

The expenses as a result of labour and production downtime can be calculated using the following equations respectively:

$$C_{inst}^{labour} = l_{rt/day} \times N_{md-inst} \quad (10)$$

$$C_{inst}^{downtime} = C_{pl/day} \times N_{dd-inst} \quad (11)$$

where $l_{rt/day}$ represents the labour rate per day, $N_{md-inst}$ represents the number of man-days required for installation, $C_{pl/day}$ represents the cost of production lost per day and $N_{dd-inst}$ represents the number of downtime days as a result of installation. Expenses related to logistics involve vessel hire, spare part costs, crew transport and cost of consumables.

The cost of production lost per day, $C_{pl/day}$ can further be calculated using the following equation (Animah et al. 2018):

$$C_{pl/day} = PR_{BOPD} \times C_P \times (1 - A_{NCBM}) \quad (12)$$

where PR_{BOPD} represents the rate of production in barrels of oil per day, C_P represents the cost of a unit of production and A_{NCBM} represents the average system availability of the equipment.

3.1.3 Operation and Maintenance of CMS

In addition to the initial acquisition and installation costs, there are expenses associated with the operation of the new maintenance regime. This includes provision of personnel training on operation of monitoring systems and complex data analysis; upgrading and maintenance of hardware and recurring licensing costs for health management software. Cost of O&M of CBM components can be given by the following equation:

$$C_{OPEX} = C_{Labour} + C_{upgrade} + C_{licensing} \quad (13)$$

where C_{OPEX} is the cost of operation and maintenance; C_{Labour} is the cost of labour required for the operation of the CBM system; and $C_{upgrade}$ is the cost of upgrading hardware.

3.2 Benefits of implementing CBM

The benefits of implementing CBM range from the tangible to intangible benefits. Tangible benefits include cost savings from reduced maintenance actions and increased revenue as a result of increased production. Intangible benefits are more difficult to analyse in a traditional cost-benefit exercise as some of the variables considered are less measurable than pure asset performance characteristics (Mobley 2001). Examples include improved overall safety, improved reputation and avoidance of environmental damage. For this CBA, only tangible benefits can and will be considered.

3.2.1 Reduction in maintenance costs

CBM involves considerably less maintenance interventions as the incorporation of condition monitoring technology allows for the ability to determine when maintenance is needed based on the condition of the equipment rather than when failure occurs, as is the case with corrective maintenance or when inspections are scheduled, as is the case with preventive maintenance. This is important as the costs of corrective maintenance tasks are, on average, considerably more than maintenance costs for tasks associated with CBM (Saranga and Knezevic, 2001). This benefit also includes reduction in maintenance costs associated with secondary damage as allowing some components to fail can also compromise other components, leading to more repair costs than anticipated. The decrease in number of maintenance actions directly results in a decrease in maintenance cost and can be considered as tangible income. The benefit can be quantified using the following equation:

$$B_{MTC} = (C_{Maint-old} \times N_M) - (C_{Maint-CBM} \times N_M)\,, \quad (14)$$

where B_{MTC} is the total benefit associated with reduction in maintenance task costs, $C_{Maint-old}$ is the maintenance task cost associated with the old maintenance regime, $C_{Maint-CBM}$ is the maintenance task cost associated with CBM, and N_M is the number of maintenance tasks.

3.2.2 Revenue from increased availability

According to Mobley (2001), the incorporation of CBM strategy has also been proven to result in less equipment downtime which in turn leads to increased revenue from production. This can be calculated as:

$$B_{IA} = PR_{BOPD} \times (A_{CBM} - A_{NCBM}) \, , \tag{15}$$

Where B_{IA} represents the benefit as a result of increased availability, A_{CBM} represents the system availability when CBM is implemented and A_{NCBM} represents system availability when CBM is not implemented.

The total benefit as a result of implementing CBM can then be calculated as:

$$B_{Total} = B_{MTC} + B_{IA} \tag{16}$$

3.3 Application case

This section discusses a case study involving a multiplex electro-hydraulic (MUX) subsea blowout preventer which is located on a semisubmersible rig. The BOP contains 2 annular preventers, 8 choke and kill valves, 2 blind shear rams and 4 variable pipe rams (Holand and Awan, 2012). The condition monitoring system which has been proposed for this BOP is the Rigsentry CMS, a product of National Oilwell Varco (NOV). The Rigsentry is both DNVGL and ABS certified for monitoring the condition of subsea and drilling services and also consists of all hardware, software and training required for consequential condition monitoring data analysis *(https://www.nov.com/misc/rigsentry)*. It performs prognostic health management and determines precursors to component failures using predictive analysis models. It also creates customised maintenance plans which accurately represent the condition of the BOP. This consequently helps to lengthen the maintenance windows and reduce the expense on spare parts.

The NPV and BCR techniques will be used to perform the cost benefit analysis for this application case. The financial and non-financial data used for this study has been accumulated from literature, company databases and expert elicitation. Table 1 below shows a summary of the total costs and benefits which has been used for the cost benefit analysis.

Table 1 Data for case study [Source: National Oilwell Varco]

Parameters	**Value**	**Unit**
$C_{aq-Total}$	209,000	GBP
C_{inst}		
C_{OPEX}	494,000	GBP
B_{Total}	932,715	GBP
i	7	%
T	10 years	Years

Based on the data obtained for this case study, the total cost of acquisition and total cost of installation are combined and considered as the total initial investment for CBM implementation. In addition, the annual expenditure for operating the CMS consists of service support, yearly software subscription fee and physical rig inspections.

The NPV for this investment was calculated using Eq. (1) as £981,508.5. This indicates that the investment in CBM implementation for subsea BOPs is financially beneficial. The BCR was also calculated using Eq. (3) as 1.77, signifying that the benefits of an investment in CBM for BOPs outstrip the costs.

A sensitivity analysis is conducted to assess the robustness of the analysis performed. This was done by varying the discount rate on both NPV and BCR equations. As can be seen in figure 2 and figure 3 respectively, a 20% increase in the discount rate yields a decrease in both the NPV and BCR while a 20% decrease in the discount rate yields an increase in the NPV and BCR.

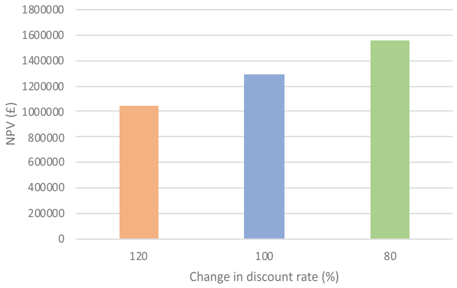

Figure 2 Effect of variation in discount rate on NPV

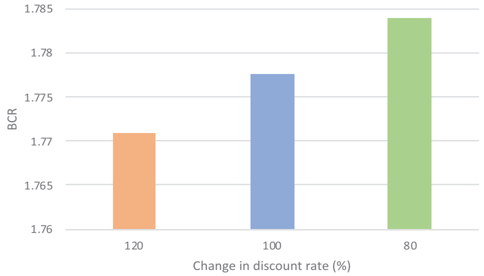

Figure 3 Effect of variation in discount rate on BCR

4 Conclusion and Further Works

In this study, a CBA on implementation of CBM in subsea BOPs was performed. The expenses and benefits associated with the implementation of CBM in subsea BOPs were identified with corresponding equations outlined in detail. The NPV and BCR techniques were applied to a case study with both confirming the economic viability of CBM implementation in subsea BOPs. A sensitivity analysis was conducted to determine the effect of changing the discount rate on the NPV and BCR.

Further work can be done to perform similar economic analysis on other subsea production systems. This analysis can also be extended to include non-economic factors such as safety and reputation. In addition, a study on the audit of the entire subsea BOP in relation to CBM implementation can be conducted in order to highlight critical components to be monitored and monitoring techniques to be applied.

References

Amin, R.A. 2016. "*Condition Based Maintenance: Innovation in Building Maintenance Management*", PhD Thesis, University College London, UK.

Animah, I., Shafiee, M., Simms, N., Erkoyuncu, J.A. and Maiti, J. 2018. "Selection of the Most Suitable Life Extension Strategy for Ageing Offshore Assets Using a Life-Cycle Cost-Benefit Approach." *Journal of Quality in Maintenance Engineering* 24 (3): 311–30.

Belyadi, H., Fathi, E. and Belyadi, F. 2016. *Hydraulic Fracturing in Unconventional Reservoirs - Theories, Operations, and Economic Analysis*. First Edition, Gulf Professional Publishing, ISBN: 9780128498620.

Børresen, C.S. 2011. "A Framework for Cost-Benefit Analysis on Use of Condition Based Maintenance in an IO Perspective." MSc Thesis, Norwegian University of Science and Technology (NTNU). https://core.ac.uk/download/pdf/52099615.pdf.

British Standard Institute. 2001. *BS ISO 15663-2: Petroleum and Natural Gas Industries - Life Cycle Costing - Part 2: Guidance on Application of Methodology and Calculation Methods*. *Standards*. Vol. 3.

British Standards Institute. 2018. *BS ISO 17359:2018. Condition Monitoring and Diagnostics of Machines — General Guidelines*. BSI Standards Limited.

Carter, K. M., Oort, E. V. and Barendrecht, A. 2014. "Improved Regulatory Oversight Using Real-Time Data Monitoring Technologies in the Wake of Macondo." In: SPE Deepwater Drilling and Completions Conference, 10-11 September, Galveston, Texas, USA.

Elusakin, T, and Shafiee, M. 2020. "Reliability Analysis of Subsea Blowout Preventers with Condition-Based Maintenance Using Stochastic Petri Nets." *Journal of Loss Prevention in the Process Industries*, 104026. https://doi.org/10.1016/j.jlp.2019.104026.

Elusakin, T, Shafiee, M, and Adedipe, T. 2019. "Towards Implementing Condition-Based Maintenance (CBM) Policy for Offshore Blowout Preventer (BOP) System." In: *38th International Conference on Ocean, Offshore and Arctic Engineering*. June 9–14, Glasgow, UK.

Gillespie, A. 2015. "Condition Based Maintenance : Theory , Methodology , & Application." In *Conference: Reliability and Maintainability Symposium*. Tarpon Springs, FL.

Gugaliya, A. and Naikan, V.N.A. 2019. "A Model for Financial Viability of Implementation of Condition Based Maintenance for Induction Motors." *Journal of Quality in Maintenance Engineering*, 26(2), 213–230.

Hess, S., Biter, W., and Hollingsworth, S.D. 2001. "An Evaluation Method for Application of Condition-Based Maintenance Technologies." In *Proceedings of Annual Reliability and Maintainability Symposium and International Symposium on Product Quality and Integrity*, 22-25 January, Philadelphia, USA.

Holand, P. and Hammad A. 2012. "Reliability of Deepwater Subsea BOP Systems and Well Kicks Unrestricted Version." www.exprosoft.com.

IAEA. 2007. "Implementation Strategies and Tools for Condition Based Maintenance at Nuclear Power Plants." Vienna. https://doi.org/10.1016/B978-0-12-398277-3.50018-X.

Kull, D., Mechler, R. and Hochrainer-Stigler, S. 2013. "Probabilistic Cost-Benefit Analysis of Disaster Risk Management in a Development Context." *Disasters* 37 (3): 374–400.

Lebold, M., Reichard, K., Byington, C.S. and Orsagh, R. 2002. "OSA-CBM Architecture Development with Emphasis on XML Implementations." In *Maintenance and Reliability Conference (MARCON)*, May 6-8, Knoxville, Tennessee, USA.

Liu, Z., Liu, Y., Cai, B., Zhang, D. and Zheng, C. 2015. "Dynamic Bayesian Network Modeling of Reliability of Subsea Blowout Preventer Stack in Presence of Common Cause Failures." *Journal of Loss Prevention in the Process Industries* 38: 58–66.

Mishan, E.J, and Euston Q. 2007. *Cost Benefit Analysis*. 5th Editio. Routledge.

Mobley, R Keith. 2001. *An Introduction to Predictive Maintenance*. Second Edi. Butterworth-Heinemann.

Mutlu, M., Wassar, T., Franchek, M.A., Omrani, A.E. and Gutierrez, J.A. 2018. "Real-Time Condition and Performance Monitoring of a Subsea BOP Pipe Ram." *SPE Drilling & Completion*, 33(1), 13 pages.

Rahim, Y., Refsdal, I. and Kenett, R.S. 2010. "The 5C Model: A New Approach to Asset Integrity Management." *International Journal of Pressure Vessels and Piping* 87: 88–93.

Rajan, B.S. and Roylance, B.J. 2000. "Condition-Based Maintenance : A Systematic Method for Counting the Cost and Assessing the Benefits." *Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering* 214 (2): 97–108.

Rastegari, A. and Bengtsson, M. 2015. "Cost Effectiveness of Condition Based Maintenance in Manufacturing." In *Proceedings of Annual Reliability and Maintainability Symposium*, 26-29 January, Palm Harbour, USA.

Saranga, H., and Knezevic, J. 2001. "Reliability Prediction for Condition-Based Maintained Systems." *Reliability Engineering and System Safety* 71(2): 219–24.

Sattler, J.P. 2013. "BOP Performance Post - Macondo - How Are We Doing?" In *SPE Arctic and Extreme Environments Technical Conference and Exhibition*, 15-17 October, Moscow, Russia.

Shafiee, M. 2015. "Maintenance Strategy Selection Problem: An MCDM Overview." *Journal of Quality in Maintenance Engineering* 21(4), 378–402.

Shafiee, M., Animah, I., Alkali, B. and Baglee, D. 2019. "Decision Support Methods and Applications in the Upstream Oil and Gas Sector." *Journal of Petroleum Science and Engineering*, 173, 1173–1186.

Shafiee, M., Elusakin, T. and Enjema, E. 2020. "Subsea Blowout Preventer (BOP): Design, Reliability, Testing, Deployment, and Operation and Maintenance Challenges." *Journal of Loss Prevention in the Process Industries*. DOI: 10.1016/j.jlp.2020.104170.

Thurston, M. 2001. "An Open Standard for Web-Based Condition-Based Maintenance System." In *Proceedings of IEEE Systems Readiness Technology Conference*, 20-23 August, Valley Forge, USA.

Turner, A. and Loustau, P. 2015. "Fiber Optic Sensor Based Monitoring System for Blowout Preventer." In *Offshore Technology Conference*, 04-07 May, Houston, Texas, USA.

Xiu, L., Juan, L., Xiu-Rong, C., Xiao-Sheng, S., Dan-Song, Y. and Xue, Y. 2015. "Lifetime Prognosis of Blowout Preventer Valve for Offshore Platform Based on Wiener Process." In *The 27th Chinese Control and Decision Conference* 23-25 May, Qingdao, China.