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Optimal Service Points (OSP) for PHM Enabled Condition Based Maintenance for Oil & Gas Applications

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ABSTRACT

In recent years, various Original Equipment Manufacturers (OEM) have started to provide different service offerings using data driven methods to enable condition monitoring of assets used in oil and gas operations. However, a significant part of the value proposition to operators focuses on value generated at the component level, with a derived reduction in asset downtime. This limits the broad economic benefits that a condition-based maintenance approach can provide, at the enterprise level. This paper therefore provides a cost benefit analysis framework that utilizes a combined technical-economic approach to determine the minimum requirements for implementing condition-based maintenance for an oil and gas asset. The framework uses prognostic algorithms for fault detection and overall system performance.

The case study tackled a set of valves in a typical Christmas tree subsystem and it showed that a prognostic enabled system provides commercial benefits at the component level and act as an enabler for CBM implementation. However, the cash flows generated at the component level becomes commercially viable when its discounted form offsets the CBM integration cost at the enterprise level. Secondly, the maintenance cost of assets, as well as the enterprise level profitability is directly influenced by the nature of failure distribution and PHM system performance, respectively. Finally, enterprise level financial viability, as well as OEM profitability in CBM implementation, requires an Optimal Service Point (OSP). This is a function of the minimum predictive requirement of the PHM system and serves as a basis for a service based business model and the identification of the technical requirements for the PHM capability.

1. INTRODUCTION

For several decades, the global energy industry has evolved from a technological standpoint to meet demand pressures from the wider global community, that depend on oil and gas products to meet their energy needs. This has been achieved through investments in new technologies by Oil and Gas companies (OGC), that maximize hydrocarbon production from subsurface formations by limiting the avoidable loss of production as well as improving the overall health and safety regime for an oil and gas project. However, the industry has faced several challenges in recent times resulting from a tightening climate change policy environment on oil and gas exploration, as well as the increasing risk of oversupply, due to new discoveries globally.

In exploring cost mitigation strategies, different maintenance policies are employed by OGCs to enhance availability of assets, as well as system reliability consequently reducing downtime, cost and waste. Incorporating these policies into oil and gas operations require assessing the additional technical improvements they add to already existing assets as well as their associated costs. A common maintenance approach used in the oil and gas industry is the preventive approach which is a remarkable improvement over the hitherto reactive maintenance approach. Recent trends in system reliability analysis in several industries show a gradual push towards the use of condition monitoring strategies, premised on system prognostics and data analytics as enablers for planning maintenance activities.

Since incorporating any maintenance strategy has cashflow implications for operators, a strong business case therefore ought to be articulated for integrating systems that enhance condition monitoring of assets used in oil and gas operations. This requires a financial analysis appraisal process that is not limited to only nominal or discounted cash flows but also a comparative framework that provides factors required for enterprise level profitability with the integration of condition-based maintenance strategies for oil and gas assets.

2. OBJECTIVES OF STUDY

The goal of this paper is to explore the optimal conditions required for a viable servitization business model for the integration of a PHM enabled condition-based maintenance strategy as part of an oil and gas project from exploration to abandonment. In the following, the objectives of this work are shown below:

- To model a predictive based PHM enabled maintenance strategy capable of detecting failure events in valves part of a Christmas tree equipment.
- To determine the financial implications of implementing the condition-based strategy at an enterprise level compared to a baseline strategy.
- To determine the optimal service points required for a mutually beneficial business model for both an Original Equipment Manufacturer and an Operator.

3. CBM IMPLEMENTATION – REVIEW AND GAPS

3.1. Condition Based Maintenance

Condition monitoring has become a critical part of industrial process monitoring as well as health and safety management for many industries around the world. The ability to accurately determine the health status of various components of a plant leads to significant improvement in decision making in maintenance management, reducing prolonged downtime and enhancing production efficiency. Condition-based maintenance (CBM) recommends maintenance decisions based on processed data from a supervisory control and data acquisition (SCADA) system (Jardine et al, 2006). A CBM strategy can significantly reduce the amount of resources incurred on maintenance downtime costs when the scheduled preventive maintenance is transformed towards a predictive strategy culminating into the realization of maintenance credits (Nico & Volker, 2015) which corroborates Gao et al. (2018)'s assessment of CBM methodology as achieving better risk control as well as return on investments on maintenance.

The research study by Wang & Li (2010) focuses on capabilities of prognostic enabled systems including fault detectability, fault isolation and prognosis of Remaining Useful Life (RUL). Their methodology provides from a life cycle assessment viewpoint, a method of PHM system validation based on analysis and simulation. Luna (2009) also explores different types of impacts and gains a PHM enabled system can have from a logistics perspective. His work also shows how extending the RUL and reducing maintenance frequency by transitioning to a CBM from a Time-based Maintenance (TBM) using system prognostics can reduce maintenance costs. Animah & Shafiee (2018) expanded on the concept of RUL specifically in oil and gas applications where they propose a systematic framework to aid stakeholders to meet Life Extension (LE) requirements while minimizing their cost. Their work points to the various factors that influence the RUL in the maintenance decision-making process.

3.2. Deployment of Product Service Solutions

Various companies are motivated by the potential commercial and technical benefits new technologies can create by making available new sources of value. Cavalieri & Pezzotta (2012) explores the various service-oriented business models that companies employ to acquire various engineering systems for the many industrial processes that are relevant for their productivity. Their work holistically analyses Service Engineering with a specific focus on its adoption in the context of a Product Service Solution (PSS) which Baines et al. (2007) defined as an integrated combination of products and services where the emphasis is put on the 'sale of use' rather than the 'sale of a product'. It is worth noting that, a servitization model for product service delivery has numerous benefits such as increased revenue and this is an observation that Gebauer et. al (2005); Gebauer et. al (2007) and Reim et al (2015) point to, which is a view that Cavalieri & Pezzotta (2012) also reinforce in their analysis of engineering service systems.

In their work, Grubic et al. (2009) also show the nexus between PSS and prognostics enabled systems in terms of the benefits that are generated. Feldman et al. (2009) and Grubic et al. (2009) provide the foundation for distinguishing between engineering service implementation models for health management systems geared towards overall system improvement. This is significant because it provides the logical basis for qualitatively characterizing the implementation costs for prognostic enabled systems as well as quantitatively determining the consequences on the value that the system can produce.

3.3. Cost Benefit Analysis (CBA) of PHM Enabled Systems

Due to the capital intensive nature of the business, Oil & Gas operators require sustained investments in operations to improve productivity and also maximize profitability. These investments require a careful review of the trade-off between the costs of implementing the investment decision and the benefits associated with it. A CBA, therefore, provides a tool for quantifying this trade-off using a standardized metric or reference which allows the viability of investment decisions to be determined (Boadman, 2018) and (European Commission, 2014). Yang & Blyth (2007) explains the traditional forms of CBA's based on payback as well as discounted cashflows. They go ahead to show the limitations in the discounted cash flow methodology in investı appraisal where the inherent assumption of the certainty of future cash flows is questioned from the fact that future risks in cash flow cannot be fully accounted for by the discount rate. Their methodology provides a model for developing a cost-benefit analysis framework for different industries based on the nature of the generation of cashflows. To account for uncertainty, French & Gabrielli (2005) demonstrate how probability analysis can be incorporated to assess current, as well as future uncertainty, in investment appraisal or capital budgeting analysis processes.

The study by Gao et al. (2018) provide a lifecycle cost analysis of subsea oil and gas valves by performing a cost-benefit analysis of PHM integration in subsea application. The quantification of downtime cost for a system with and without PHM functionality is very useful, because it provides an avenue for scaling up the benefits of a prognostic enabled oil and gas system beyond the component level to assess the financial impact at the enterprise level, for an Oil & Gas Field Development Project (OGFDP). Sandborn & Wilkinson (2007), Ghosh & Roy (2009), Haddad, Sandborn & Pecht (2012), Compare, Bellani & Zio (2017); Gao et al. (2018) have all explored the probabilistic modelling for CBA of various systems. Padgett et al. (2010) and Mondoro et al (2018) point to the common output financial metric−Benefit to Cost Ratio (BCR) and Net Present Value (NPV)− for supporting asset management.

3.4. Research gaps

The review of existing literature on CBA approaches for PHM enabled systems revealed two main gaps. An assessment of all the literature reviewed showed significant emphasis on developing cost-benefit analysis frameworks or models for aerospace and electronic systems in the context of the application of PHM systems. Very few of the papers looked at oil and gas assets and hence there is the need to broaden the scope of the PHM cost/benefit approaches for oil and gas surface applications. Also, the quantification of the output metrics of the CBA models was done mostly at the component or subsystem level and hardly at the enterprise level with respect to the impact of a PHM enabled system on maintenance approaches. This paper provides the development of a cost-benefit analysis (CBA) framework for the implementation of an optimal business case for a prognostic enabled CBM strategy for valves used in oil and gas surface applications.

4. METHODOLOGY

The methodology proposed in this section provides a framework that utilizes a combined technical-economic approach to determine the minimum predictive requirement for implementing condition-based principles for maintenance of assets in a hydrocarbon project from first oil to abandonment.

4.1. Valve Degradation Modelling

4.1.1. Surface Production System

A wellhead/Christmas tree assembly is one of the main components of an onshore oil and gas field (OGF) production system. The wellhead and the Christmas Tree subsystems perform distinct functions, the former provides pressure control during drilling and production operations as well as serve as the nexus between the well and a surface control equipment. The latter controls the flow of hydrocarbons out of the wellbore (Guo et al, 2017). In this paper, the focus would be on valves that form an integral part of the surface Christmas tree (XT). Four (4) valves would be used for this analysis, using critical failure modes under a specific failure distribution, to model the occurrence of failure events over the operational life of each valve.

4.1.2. Valve Failure Modes and Degradation

Valves used in oil and gas field operations are expected to degrade over time as the production of hydrocarbons in-situ presents harsh operating conditions for plant and equipment used by most field operators. Stakeholders in the oil and gas industry use various forms of asset qualification and reliability analysis to identify the various functional failure modes of assets gaining enough insight into failure mechanisms, causes as well as detection methods. In this report, valve data from Gao et al (2018) where the number of critical failures of each valve, N was used to model the sequencing of a failure event occurring using a probability distribution. A Weibull distribution using three cases with a constant scale factor (ScF) and varying shape factors (SF) is used for the failure distribution associated to each valve. Figure 1 shows a block diagram detailing the failure distribution modelling for the valves while the parameter Failure Load (FL) shows the percentage of the faults that occur in the operational life of the valve based on a failure probability distribution see Eq. (1). This valve degradation model is however done specifically for the CBM approach.

$$FL = \frac{Number\ of\ Faults\ that\ occur}{Critical\ Failures(N) \times Number\ of\ Assets(NA)} \tag{1}$$

$$Failure\ Modes\ Detected = FL \times N \times NA \tag{2}$$

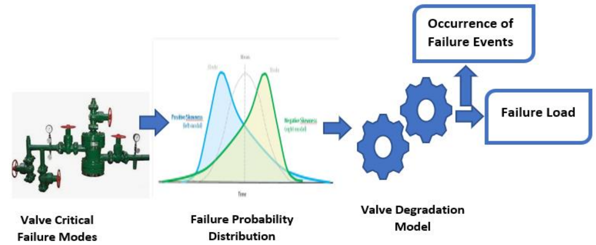

Figure 1: Valve degradation modelling for CBM

4.2. Assessment of Cost for Maintenance Approaches

4.2.1. Time Based Maintenance (TBM)

The scheduled maintenance approach is premised on carrying out maintenance activities based on discrete, interval-based events (Nico et al, 2015). The time-based maintenance (TBM) strategy would serve as a baseline maintenance approach and compared with the condition-based maintenance (CBM). Using a Weibull distribution with a constant failure rate to model the failures for the TBM approach, Eq. (3) is used to determine the maintenance cost for the valves being considered where T is the operational life of the asset, *Tser* is the number of activities carried out per year, *Cm* is the cost of repair, *Cr* is the cost of replacement and λ is the failure rate (Ghosh & Roy, 2009). Equation (4) provides the cost in terms of production loss while Eq. (5) sums up the total downtime cost.

$$C(T) = \frac{T_{ser}}{T}\left[C_m e^{\lambda T} + C_r\left(1 - e^{-\lambda T}\right)\right] \tag{3}$$

$$P(T) = Number\ of\ Fixed\ Maintenance\ Activities \times Output\ Loss\ per\ activity \tag{4}$$

$$D(T) = CT + P(T) \tag{5}$$

4.2.2. Condition Based Maintenance (CBM)

A condition-based maintenance approach unlike TBM optimizes the usage of the remaining useful life of an asset by using prognostics to monitor and predict potential failure events. End-users of condition monitoring systems may adopt a PSS based on a servitization model where a contractor or service provider carries out maintenance activities on behalf of an operator. The nature of a maintenance strategy adopted by an operator has a direct impact on the financial outcomes of an oil and gas project. This has cost implications in relation to downtime costs, as well as repair and replacement of specific components of the asset. The analysis of maintenance cost for valves based on PHM capability by (Gao et al, 2018) was adapted to determine the maintenance costs, as well as loss of production for an oil and gas field life cycle. Equations (6) and (7) are used to determine the cost of scheduled and unscheduled repair respectively.

$$S_R = \left\{\left(MTTR_{Repair} \times h_s\right) + \left(MS \times N_{days}\right) + S_{sm}\right\} \times \left(N_{failure} \times N_{components} \times PHM_{coverage}\right) \tag{6}$$

$$U_R = \left\{\left(MTTR_{Repair} \times h_{us}\right) + \left(MS \times N_{days}\right) + S_{um}\right\} \times \left(N_{failure} \times N_{components} \times \left(1 - PHM_{coverage}\right)\right) \tag{7}$$

The cost of replacing assets during maintenance activities is also influenced by the asset monitoring strategy used and Eqs. (8) and (9) are used to determine the cost of a scheduled and unscheduled replacement of an asset respectively.

$$S_r = \left\{\left(MTTR_{Replace} \times h_s\right) + \left(MS \times N_{days}\right) + M_{cost} + S_{sm}\right\} \times \left(N_{components} \times PHM_{coverage}\right) \tag{8}$$

$$U_r = \left\{\left(MTTR_{Replace} \times h_{us}\right) + \left(MS \times N_{days}\right) + M_{cost} + S_{um}\right\} \times \left(N_{components} \times \left(1 - PHM_{coverage}\right)\right) \tag{9}$$

Repair and replacement activities on oil and gas assets have cost implications on the operations. The more directly an asset is linked to the production of hydrocarbon fluids, the more productivity is lost when maintenance has to be carried out on that particular asset. Equation (10) shows how the value lost for an oil field production as well as gas is determined where D is the downtime associated with either repair or replacement activities. For any maintenance strategy, the extent of downtime is directly proportional to the value of the potential hydrocarbon volume that could have been produced. Equations (11) to (14) are used to determine the value of productivity lost for a CBM strategy during repair and replacement activities. Equations (11) and (12) are used for productions loss due to scheduled repair and replacement, respectively, while Eqs. (13) and (14) are used for unscheduled repair and replacement, respectively.

$$Output_{loss} = D \times \left\{\left(Oil_{vol/hr} \times Price_{oil}\right) + \left(Gas_{vol/hr} \times Price_{gas}\right)\right\} \tag{10}$$

$$SL_{Repair} = Output_{loss} \times N_{components} \times N_{failure} \times PHM_{coverage} \tag{11}$$

$$SL_{Replace} = Output_{loss} \times N_{components} \times PHM_{coverage} \tag{12}$$

$$PSL_{Repair} = Output_{loss} \times N_{components} \times N_{failure} \times \left(1 - PHM_{coverage}\right) \tag{13}$$

$$PSL_{Replace} = Output_{loss} \times N_{components} \times \left(1 - PHM_{coverage}\right) \tag{14}$$

Equations (15) and (16) show how the total maintenance cost associated with ensuring the availability of an asset as well as the loss of revenue due to loss of production can be determined.

$$T_{Maintenance\ Cost} = S_R + S_r + U_R + U_r \tag{15}$$

$$T_{loss\ of\ production} = SL_{Repair} + SL_{Replace} + PSL_{Repair} + PSL_{Replace} \tag{16}$$

Consequently, the total downtime cost to an operator would be the sum of the maintenance cost and the cost of output loss. see Eq. (17).

$$Total_{Downtime\ Cost} = T_{Maintenance\ Cost} + T_{loss\ of\ production} \tag{17}$$

4.3. CBM Implementation Cost Modelling

4.3.1. Implementation Costs

Valves are instrumental for hydrocarbon production as their availability directly impacts production from reservoirs and ultimately affecting the profitability of the project. Therefore, implementing a condition-based strategy is vital to the profitability of an oil and gas project but such a strategy would require three main forms of implementation cost. A condition-based system would require investments in recurring or nonrecurring costs as well as sustainment costs. This paper utilizes Eq. (18) which shows the total cost associated with implementing a maintenance strategy where C_{REC} is the recurring cost and C_{NRE} is the nonrecurring cost while C_{INF} is the sustainment required cost (Feldman et al, 2009).

$$I_{CPM} = C_{NRE} + C_{REC} + C_{INF} \tag{18}$$

4.3.2. Cost Avoidance

Limiting the loss of production output resulting from unplanned downtime due to the degradation of an asset depends on the type of maintenance approach adopted by an operator. The difference in cost between the TBM approach and a CBM approach results in avoiding the cost associated with the former. The cost avoided by implementing a maintenance strategy is a function of the sequencing of the various failure modes of the assets. Equation (19) shows the cost savings for a prognostic enabled CBM strategy where C_U is the cost of a baseline approach and C_{CPM} the cost of a condition-based strategy. Equation (20) is used to determine the return on investment for a particular maintenance strategy where $ROI > 0$ is a viable value proposition (Feldman et al, 2009)

$$CA = C_U - C_{CPM} \tag{19}$$

$$ROI = \frac{CA}{I_{CPM}} \tag{20}$$

4.4. Project Lifecycle Cost Modelling

Oil and gas projects by their nature are high risk and capital-intensive ventures with significant environmental implications. These projects are developed in phases, from exploration and appraisal to abandonment. These phases are categorized into two main forms of project lifecycle costs, capital expenditure as well as operational and maintenance expenditure. Minimizing these project lifecycle costs for an oil and gas project improves the overall financial outcomes such as cashflows, as well as internal rate of return.

4.4.1. Capital Expenditure (CAPEX)

The capital expenditure required for a typical oil and gas field development covers the cost needed for the exploration and appraisal which enables the discovery and quantification of hydrocarbons in-situ. Field development then continues with the drilling of wells as well as the installation of a platform for hydrocarbon production to begin and when the field reaches abandonment phase operators incur abandonment cost.

$$CAPEX = C_{E\&A} + C_{Drilling\ \&\ Platform} + C_{P\&E} + C_{Abandonment} \tag{21}$$

4.4.2. Operations and Maintenance

Ensuring the efficient production of hydrocarbons from reservoirs aside the initial capital investment required to set up the infrastructure, there is also the need for sufficient resources to be allocated to ensure operational as well as maintenance activities are carried out. The cost of running the daily operations includes compensation for fulltime and contracted workers which forms a key part of the operational cost of managing an oil field. Ensuring that components of systems and subsystems are available for efficient and consistent production of hydrocarbons form part of the required activities needed for operational efficiency. Maintenance activities are therefore carried out periodically or based on system condition to ensure that system availability is optimized.

$$C_{O\&M} = C_{Operational\ Expenditure} + C_{Maintenance} \tag{22}$$

4.4.3. Project Revenue

The revenue generated from an oil and gas project depends on the type of reservoir being exploited and the field products being prioritized such as oil, gas or condensate. The total revenue for the field directly depends on the product of the volume of hydrocarbons being produced at a given time and the prevailing market or futures price for that particular hydrocarbon. In this study, the Buildup-Plateau-Decline (BPD) production profile is used for modelling the oil field production of hydrocarbons (see Figure 2).

$$PROJECT_{REVENUE} = Hydrocarbon_{Volume} \times Price_{Hydrocarbon} \tag{23}$$

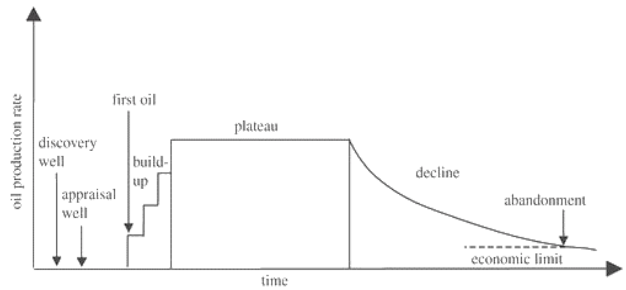

Figure 2: Hydrocarbon Production Profile (Höök et al., 2009)

4.5. Financial Analysis

The adoption of any new technology by businesses for their operations requires a viable business case for the replacement of the old technology and clear improvements in the financial outcomes, at the enterprise level. Maximizing the profitability of a project through a maintenance strategy for a subsystem does not necessarily lead to optimal economic value of the system as a whole (Feldman et al, 2009). Therefore, both the CBM and TBM strategies would be analyzed based on their impact on the financial outcomes on an oil and gas project lifecycle, using a field development scenario.

4.5.1. Cashflow Analysis

The yearly net cash flows of the project for the baseline maintenance strategy compared to the net cash flows generated using a CBM approach are determined using the Eq. (24). The cash flows for the two maintenance approaches are then discounted using an oil industry discount rate to quantify all cashflows within a specific base year to determine the Net Present Values. See Eq. (25).

$$Net\ Cashflow = PROJECT_{REVENUE} - CAPEX - C_{O\&M} \quad (24)$$

$$NPV = -C_0 + \sum_{i}^{N_{abandonment}} \frac{Cashflow_{yearly}}{(1+Discount\ Rate)^i} \quad (25)$$

4.5.2. Project Payback

One of the key performance indicators of investing in an asset or a system is its payback period as this measures the rate at which the investment made in the system or asset is recouped. In the case of the field development scenario, the payback period indicates the time in the life of the field that operators break even. It is the point where the $Cumulative\ NPV = 0$ after the Maximum Capital Outlay (MCO) is reached.

$$\Delta_{Payback} = Payback_{Baseline} - Payback_{CBM} \quad (26)$$

$$MCO = Minimum\ Cumulative\ NPV \quad (27)$$

4.5.3. Profit to Investment Ratio

Another key performance indicator for investing in an asset or a system is its Profit-to-Investment Ratio (PIR) also known as Profitability Index (PI) highlights the payoff of an investment in a project and it is a viable economic tool for ranking the profitability between two comparable systems. It is a ratio of cumulative Net Present Value (NPV) and the Maximum Capital Outlay (MCO) for the project lifecycle

$$PIR = \frac{Cumulative\ NPV}{MCO} \quad (28)$$

4.5.4. Enterprise Level Cost Benefit Analysis

A CBA process would be used to evaluate the financial performance of the two maintenance approaches over the field lifecycle. The decision criteria for assessing the PHM enabled CBM approach with the TBM as baseline would be a weighted form of the Benefit-to-Cost Ratio (BCR), see Eq. (29) where the Failure Load resulting from the failure distribution is used as the weighting factor. The resulting parameter would be a Failure Load Weighted Benefit-to-Cost Ratio (FLWBCR) which would be statistically analyzed to determine the percentage of the number of instances from a Monte Carlo simulation where $FLWBCR > 0$ which would be defined as $K - Factor$, See Eq. (33) where the profitable business case is when $K - Factor > 0$. For a viable business case on the other hand, $K - Factor > 50\%$ where the risk of enterprise level loss is less than the probability of success. The commercial benefit to an OEM is defined by Eq. (35) and Eq. (34) shows how the fee an OEM charges an operator annually for providing CBM service is determined.

$$\Delta Maintenance\ Cost = \frac{MCost_{CBM} - MCost_{TBM}}{M\ Cost_{TBM}} \quad (29)$$

$$\Delta PIR = \frac{PIR_{CBM} - PIR_{TBM}}{PIR_{TBM}} \quad (30)$$

$$BCR = \frac{\Delta PIR}{\Delta Maintenance\ Cost} \quad (31)$$

$$\text{FLWBCR} = Failure\ Load \times BCR \times 100 \quad (32)$$

$$K - Factor = \frac{(\text{FLWBCR})_N > 0}{(\text{FLWBCR})_N} \times 100 \quad (33)$$

$$Annual\ Service\ Fee\ (ASF) = \frac{Total\ TBM\ Cost + ERE}{Project\ Life} \quad (34)$$

$$OEM\ Net\ Income = ASF - MC_{OEM} - IC_{OEM} - DC \quad (35)$$

$$DC = \frac{100 - PHM\ System\ Performance\ (\%)}{100} \times ASF \quad (36)$$

4.6. Monte Carlo Simulation

An appropriate probability distribution for input variables in the analysis is defined to capture the uncertainties from financial market data. This would be used in a Monte Carlo Simulation which would allow the consequences of changes in financial market data such as discount rate as well as hydrocarbon price to be incorporated into the overall enterprise-level financial analysis for the oil and gas field.

4.6.1. Optimal Service Point (OSP)

A standalone Application for the purpose of this paper called FinPHM (See Figure A1), is created using MATLAB R2020b programming software. The application provides the utility of varying several input parameters such as field and market data, failure distribution models and prognostic characteristics as well as the seamless visualization of the decision criteria. The application utilizes a supervised machine learning approach to determine the number of missed failure as well as false positive events which are used to model the performance of the PHM enabled CBM system. Data generated using the application is then used to determine the minimum value of the $K - Factor$ that an operator can use as basis for incorporating a condition-based approach in its maintenance strategy. It also provides the Annual Service Fee (ASF) derived from the cumulative OEM NPV needed for structuring and pricing servitization agreements between OEMs and operators. Figure (3) shows a block diagram which summarizes the process of determining the optimal service point for implementing the CBM strategy.

5. Case Study

5.1. Introduction

The proposed case study is intended to demonstrate that a maintenance strategy for oil and gas valves, based on a servitization model where the benefits of utilizing a CBM strategy, yields cost savings at the component level and also maximizes the commercial benefits at the enterprise level for an oil and gas project. The scenario where operators outsource the maintenance to a service provider that utilizes a CBM inspired maintenance strategy to monitory the health of the operator's assets is also analyzed.

5.2. Data and Assumptions

To perform this analysis, various valve and operational data were adapted from available literature as well as the needed assumptions were made. In this case study, surface Christmas tree valves were used mainly because of the direct consequence of their functional failure on hydrocarbon production. Four main valves of a surface Christmas tree namely kill wing valve, swab valve, flow wing valve and upper master valve are the components under investigation within this case study. It is assumed that each of the four valves have the same PHM coverage, which is indicative of the number of monitored faults with respect to the overall failure modes affecting the surface Christmas tree valves.

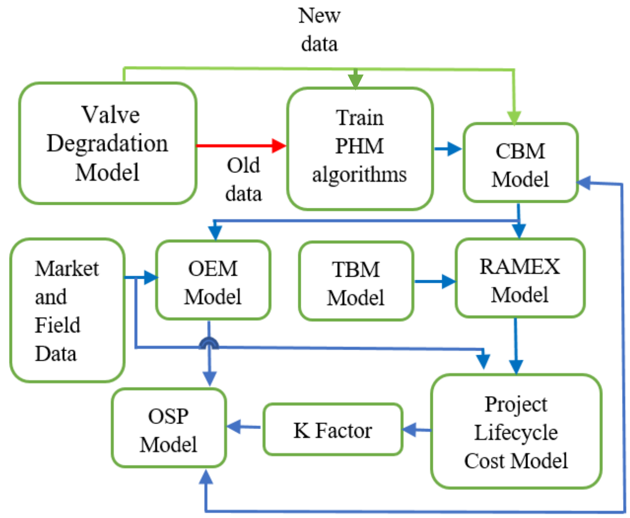

Figure 3: Block Diagram for determining OSP

Both the baseline TBM approach and the CBM approach include asset repair as well as replacement costs and these costs are a function of downtime, the logistics and the cost of the required manpower. Table (A2) shows the components needed to determine the repair and replacement costs for the surface Christmas tree valves based on OREDA data (Gao et al, 2018) with the number of critical failures assumed to be 28 due to the low risk associated with onshore operations compared with offshore operations (Deyab et al, 2017).

The recurring, non-recurring as well as the sustainment cost are each assumed to be a third of the total maintenance cost ($\frac{1}{3} \times Maintenance\ Cost$) of the surface Christmas Tree valves The downtime associated with maintaining surface Christmas tree valves involves phases such as shutdown time through mobilizing to start up time. Table (A3) shows the downtime for CBM strategy while the downtime cost modelling for the TBM approach is determined using the Weibull cost modelling in Eq. (3) with one (1) maintenance activity per year over the operational life of each valve. The capital expenditure, production data as well as tax data for an oil field development is presented below in (Figure 4). Table (A4) also shows the fiscal data used for the field development evaluation and it includes the project discount rate as well as the price of hydrocarbons. Figure (5) shows the Buildup-Plateau-Decline (BPD) hydrocarbon production profile used in this case study.

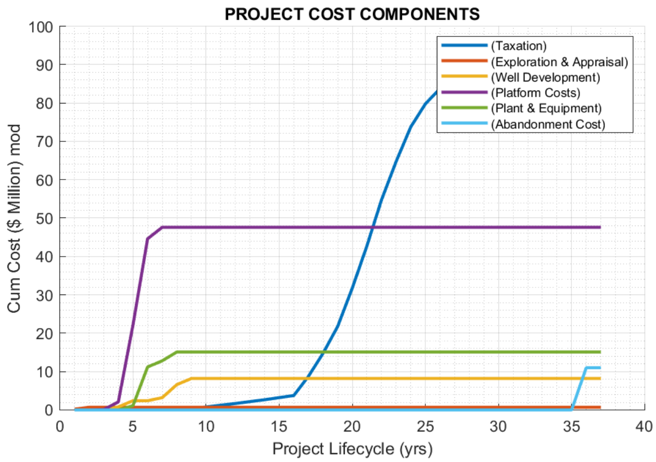

Figure 4: Project Lifecycle base information ($ Million)

5.3. Simulation Results

The 4th year is used as the base year for Net Present Value analysis for the project lifecycle. The initial simulation begins with a PHM coverage of 70% for the XT Valves using the Weibull distribution with a scale factor of 10 and a shape factor < 1 with the number of simulations (n) set at 10000. From the Weibull failure distribution model, Fig. (6) shows the number of failure events in each year of the operational life of each valve. Figure (7) then shows the prediction by the PHM algorithm where a supervised learning approach is used to predict of failure events of the valves in Fig. (6). The prediction of failure events by the FinPHM application showed one (8.51%) Missed Failure (MF) event and eight (46.09%) False Positive (FP) events by the PHM enabled CBM strategy. Representing a PHM system performance of 91.49% and 53.91 % respectively. Considering a scenario of both MF and FP, the performance of the PHM enabled system then reduces to 45.39 %. The range of oil and gas prices used are $\$27.52 < oil\ (bbl) < \$63.66$ and $\$0.75 < gas\ (\ scf) < \$4.46$ with average production of $83{,}120\ bbl/day$ and $44{,}530\ scf/day$ for both oil and gas respectively.

5.3.1. Time-based Maintenance

The maintenance cost for the baseline TBM approach using the Weibull distribution with a constant failure rate showed a characteristic decline in the maintenance cost for the set of Christmas Tree Valves under consideration. The maintenance cost for the first maintenance activity in the first year of each valve was $45,500.00 constantly declining to $12,000.00 consequently resulting in a total maintenance cost per valve for the assumed operational life of $82,500.00. An overall cost of $330,00.00 for all the four (4) valves is obtained with a maintenance savings in relation to RTF maintenance approach of $157,000.00 over the operational life of all the Christmas Tree Valves. The cash flow analysis for the TBM strategy showed average positive NPV of $7.9 billion with an MCO of $63.6 million.

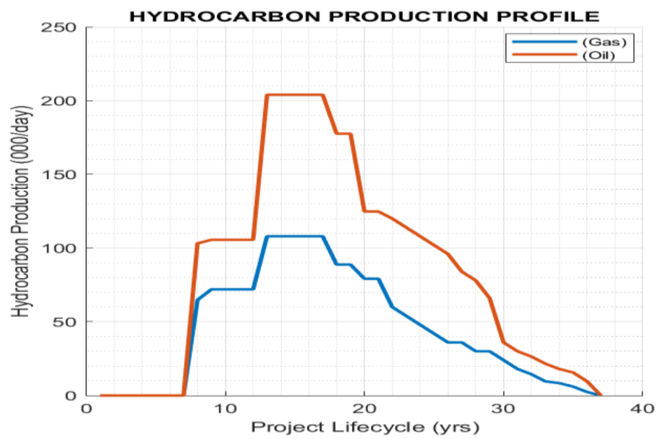

Figure 5: Hydrocarbon production for the field

5.3.2. PHM Enabled Condition based Maintenance

With a PHM system performance of 91.49% the CBM strategy saves the operator $1.076 million over the entire project lifespan in maintenance expenditure compared to the TBM. The CBM strategy increases the NPV of the project by 50.74% and the PIR by 15.4% with a $K - Factor$ of 75.11% . The system performance of 91.49% reduces an initial $1.5 million ASF by an OEM to $1.372 million per annum due to reduction in performance. With a starting PHM system development cost of $0.8 million Fig. (9) shows the cost profile for the OEM over their service agreement with an operator. The OEM therefore accrues an NPV of $\$28.51\ million$ with a payback of 10 years.

The maintenance cost of the PHM enabled system shows a higher value than the baseline approach in the early part of the project life, however, it becomes less than that of the baseline towards the end of the project (see Figure 8). This results from the impact the Buildup-Plateau-Decline (BPD) production profile has on production savings resulting from implementing a CBM strategy. In the initial stage, the operator incurs cost of integrating the CBM strategy in its operations and also paying the OEM an ASF for carrying out the CBM activity. This amounts to a significant frontloaded cost that the production savings of the initial buildup phase of the production profile does not offset. However, as production continues the production volume becomes significant enough to offset the CBM frontloaded cost.

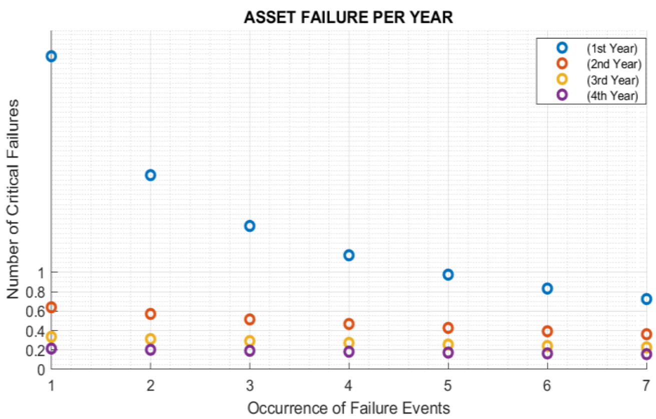

Figure 6: Number of failure of the valve that occur.

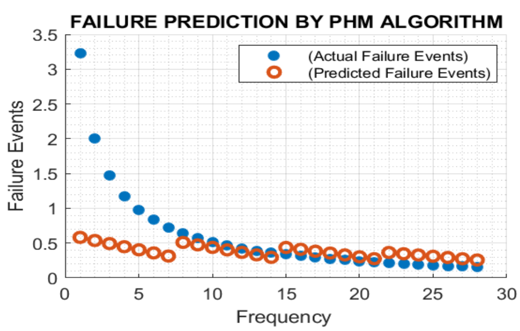

Figure 7 : Prediction of Failure events by the PHM enabled system

Table 1: Simulation Results for the PHM enabled system using a Weibull failure distribution

System Performance (%)	OEM NPV ($)	K-Factor (%)
91.49	28,511,619.00	75.11
53.91	11,601,645.00	4.73
45.39	7,771,135.00	2.85

Table 2: Simulation Results for different CBA approaches

System Performance (%)	Failure Distribution	CBA approaches			
		NPV ($B)	PIR	CBM (ROI)	K-Factor (%)
91.49	Weibull	15.93	189	1.57	75.11
86.06	Weibull	9.42	26	0.11	0.23
86.89	Normal	8.21	106	0.04	0.78

5.4. Optimal Service Point (OSP)

Figure (11) shows a plot where the enterprise level profitability as well as OEM cumulative NPV depends on the performance of the PHM enabled CBM system. Using a crossing strategy for correlated assets as a basis for a financial decision is a well-established principle in financial analysis especially intermarket analysis. For instance, the crossing of rising bond yields and declining stock indices is an indication of rising inflation which informs the allocation of financial assets (Murphy, 1991). The intersection of the OEM cumulative NPV and $K - Factor$ provides the optimal points for a CBM implementation. The minimum PHM system performance required is 89% with a starting ASF by an OEM of $0.8146 million.

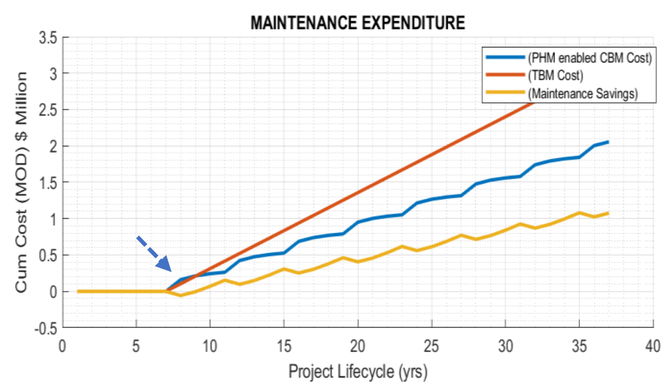

Figure 8: Additional Capital required for the CBM implementation

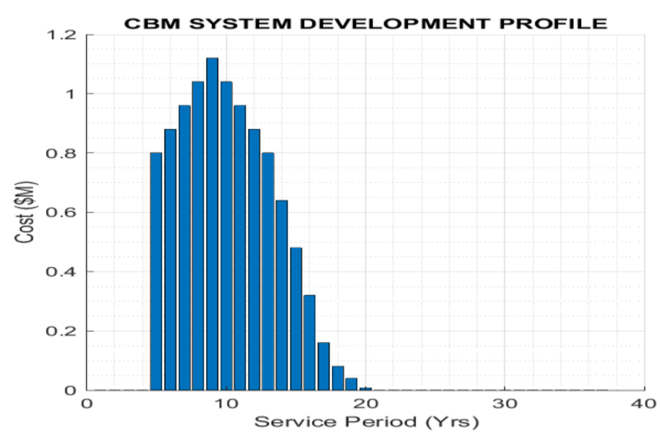

Figure 9: PHM enabled system development cost distribution

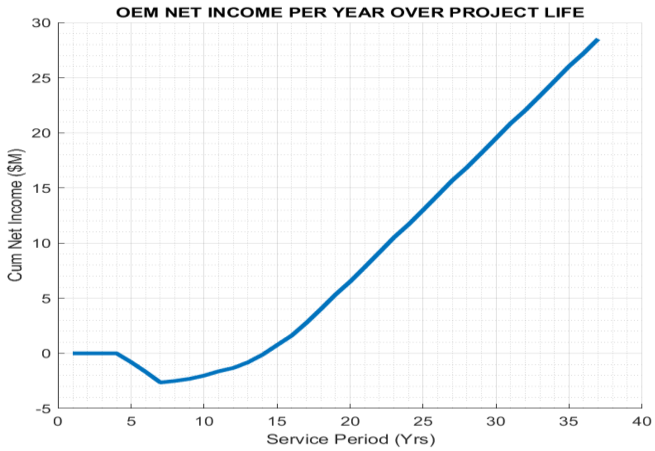

Figure 10: OEM NPV over service period

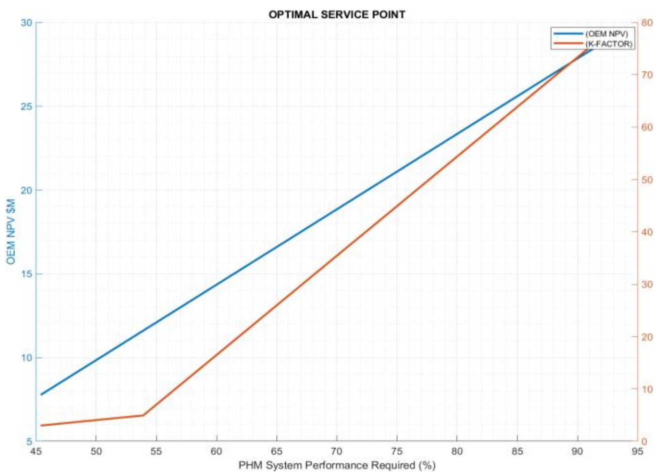

Figure 11: Optimal Service Point for CBM implementation

6. DISCUSSIONS

The ideal situation for a commercially viable PHM enabled condition based maintenance system, would require the cumulative reduction in downtime at the component level over a project lifecycle to offset the total cost of integrating a PHM enabled system into the overall maintenance strategy. The simulation results from the case study showed that the prognostic enabled condition based maintenance strategy resulted in reduction downtime cost at the component level. Table (A5) shows that for the Weibull failure distribution with a shape factor SF <1 and SF = 1, the PHM enabled system yielded maintenance savings of $1.0762 and $0.114 million respectively over the project life. The difference in maintenance savings is the result of the nature of the failure distribution of the component.

The impact of integrating a PHM enabled CBM strategy on enterprise level cash flows depends on the number of failure events occurring in the life of the valve and the accuracy of predicting them by the PHM system. Table (A5) also shows different failure distributions and PHM system performance as well as their respective $K-Factors$ which is the enterprise level profitability criterion. The effect of the number of failure events occurring on enterprise level cash flows, is seen where a PHM system performance of 86.89% and 86.06% for the mean centred normal distribution and a Weibull distribution with a SF = 1 respectively resulted in different $K-Factor$ values. The different $K-Factor$ values show that the nature of a component's failure distribution has an impact on enterprise level cash flows.

Table (2) shows the results for different CBA approaches for a Weibull as well as Normal failure distribution for the valves under consideration. The CBM ROI provides the value generated at the component level for every $1 spent on maintenance. The results show an $ROI > 0$ which indicates that the PHM enabled CBM strategy generates financial value at the component level. The $NPV, PIR \text{ and } K-Factor$ all provide different insights into enterprise level profitability for CBM implementation. The positive $NPV \text{ and } PIR$ values in Table (2) show viability at the enterprise level for CBM implementation. However, they do not provide a comparative metric for an already existing maintenance strategy. The $K-Factor$ provides this metric by using in this case a TBM as a reference to evaluate the probability of success, consequently providing the risk associated with CBM integration. The $K-Factor$ for the Weibull distribution with 91.49% system performance show a 24.89% probability that the value generated by a TBM approach is higher than that of a CBM.

The minimum PHM system performance required identified in Fig. (11) provides two key outcomes that are vital to the implementation of an optimal CBM strategy. For a performance based service arrangement between an OEM and an operator, the former can aim at a business proposition with a minimum PHM enabled system performance of 89% and an ASF of $0.8146 million. The OEM can use this information (see Figure 11) to provide a CBM service knowing the value their system would be providing. The OEM would be able to determine the enterprise level profitability using the TBM as a baseline when all other economic and technical uncertainties are factored in. On the other hand, the operator would have a benchmark for the maximum financial risk they can expose their project to by integrating a CBM strategy. The OSP therefore provides the framework for meeting both technical as well as financial requirements for the viable implementation of a CBM strategy.

7. CONCLUSION

The proposed OSP cost benefit analysis approach provides OEMs and operators with a practical guide in the provision as well as the adoption of condition-based maintenance strategies. It balances the risk of PHM integration by operators with a minimum PHM system perform threshold required for commercial viability for a project lifecycle. The significance of this paper is in two-fold, the first is its contribution to the existing body of literature that assesses the cost benefit analysis of implementing CBM strategies enabled with prognostic capabilities for asset health management for Oil and Gas applications. Secondly, setting out a OSP framework for a profitable integration of a CBM approach at the enterprise level.

Even though, in this paper, the OSP framework was instantiated for a hydrocarbon project, it can also be applied to applications from other industry sectors. Since paper used a new hydrocarbon field in the analysis of the OSP framework, further research is required to map all the parameters contributing to the assessment of the profitability of PHM capabilities for existing fields. Also, there is the need for more research using the OSP methodology for assets in different industry sectors aside oil and gas.

NOMENCLATURE

Co	Initial Investment	[$]
D	Downtime	[days]
h	Man Hours	[hr]
$MTTR$	Mean Time to Repair	[days]
S_R	Scheduled repair cost	[$]
S_{sm}	Indirect Scheduled Repair Support	[$]
S_{um}	Indirect Unscheduled Repair Support	[$]
λ	failure rate	[failure/hr]
$K - Factor$	Decision criterion	[%]
DC	Non-Performance Cost	[$]
ERE	Extra RAMEX Expenditure	[$]

REFERENCES

Ahmad, R., & Kamaruddin, S. (2012, February 18). An overview of time-based and condition-based maintenance in industrial application. *Computers & Industrial Engineering, 63*(1), 135-149. doi:https://doi.org/10.1016/j.cie.2012.02.002

Animah, I., & Shafiee, M. (2018). Condition assessment, remaining useful life prediction and life extension decision making for offshore oil and gas assets. *Journal of loss prevention in the process Industries, 53*, 17-28. doi:http://dx.doi.org/10.1016/j.jlp.2017.04.030

Boadman, A., Greenberg, D., Vining, A., & Weimer, D., (2018). Cost Benefit Analysis: Concepts and Practice., 4th edition, Cambridge University Press, DOI: 10.1017/9781108633840

Cavalieri, S., & Pezzotta, G. (2012, February). Product–Service Systems Engineering: State of the art and research challenges. *Computers in Industry, 63*, 278–288. doi:http://dx.doi.org/10.1016/j.compind.2012.02.006

Compare, M., Bellani, L., & Zio, E. (2017). Reliability model of a component equipped with PHM capabilities. *Reliability Engineering and System safety, 168*, 4-11. doi:http://dx.doi.org/10.1016/j.ress.2017.05.024

Deyab, S., Taleb-Berrouane, M., Khan, F., & Ming, Y. (2018). Failure Analysis of the offshore process component considering causation dependence. *Process Safety and Environmental Protection, 113*, 220-232.

Engel, S., Gilmartin, B., Bongort, K., & Hess, A. (March 2000). Prognostics, the Real Issues Involved with Predicting Life Remaining. (pp. pp. 457-469). Big Sky, MT: *Proceedings of the IEEE Aerospace Conference*.

European Commission. (2014). Guide to Cost-Benefit Analysis of Investment Projects. Brussels: European Commission.

Fatih Camci, G., Valentine, S., & Navarra, K. (2007). Methodologies for Integration of PHM Systems with Maintenance Data. *IEEE*.

Feldman, K., Jazouli, & Sandborn, P. (2009, June). A Methodology for Determining the Return on Investment Associated With Prognostics and Health Management. *IEEE Transactions On Reliability, 58*(2), 305-316. Retrieved June 15, 2020

Feldman, K., Peter Sandborn, P., & Jazouli, T. (2008). The Analysis ofReturn on Investment for PHM Applied to Electronic Systems. *International Conference On Prognostics And Health Management*.

French, N., & Gabrielli, L, (2005). Discounted Cashflow: Accounting for Uncertainty, *JPIF*, vol. 23(1)

Gao, X., Niculita, O., Balkali, B., & Mcglinchey, D. (2018). Cost benefit analysis of applying PHM for Subsea Applications. *European Conference Of The Prognostics And Health Management Society*.

Gebauer, H. Fleisch, E., Friedli, T., (2005). Overcoming the Service Paradox in Manufacturing Companies. *European Management Journal*, 3 (1) (2005), pp. 14-26, 10.1016/j.emj.2004.12.006

Ghosh, D., & Roy, S. (2009, January). Maintenance optimization using probabilistic cost-benefit analysis. *Journal of Loss Prevention in the Process Industries, 22*, 403–407. doi:doi:10.1016/j.jlp.2009.01.007

Guillen, A., Crespo, A., Macchi, M., & Gomez, J. (2016). On the role of Prognostics and Health Management in advanced maintenance systems. *Production Planning & Control, 27*(12), 991-1004. doi:DOI: 10.1080/09537287.2016.1171920

Haddad, G., Sandborn, P., & Pecht, M. (December 2012). An Options Approach for Decision Support of Systems With Prognostic Capabilities. *IEEE Transactions On Reliability, 61* (4).

Hölzel, N., & Gollnick, V. (2015). Cost-benefit Analysis of Prognostics and Condition-based Maintenance Concepts for Commercial Aircraft Considering Prognostic Errors. *Annual Conference Of The Prognostics And Health Management Society*.

Höök, N., Söderbergh, B., Jakobsson, K & Aleklett, K., (2009, March). The Evolution of Giant Oil Field Production Behaviour. *Natural Resources Research. , 18*(1), 39-56., doi:10.1007/s11053-009-9087-z.

Jardine, A., Lin, D., & Banjevic, D. (2006). A review on machinery diagnostics and prognostics implementing condition-based maintenance. *Mechanical Systems and Signal Processing, 20*(7), 1483-1510. doi:https://doi.org/10.1016/j.ymssp.2005.09.012.

Luna, J. (2009). Metrics, Models, and Scenarios for Evaluating PHM Effects on Logistics Support. *Annual Conference of the Prognostics and Health Management Society.* Beverly: Annual Conference of the Prognostics and Health Management Society.

Mondoro, A., Frangopol, D.M & Liu, L. (2018). Multi-criteria robust optimization framework for bridge adaptation under climate change, *Struct. Saf.*, 74, pp. 14-23, 10.1016/j.strusafe.2018.03.002

Mitchell, J., Marcel, V., & Mitchell, B. (2015). *Oil and Gas Mismatches: Finance, Investment and Climate Policy.* Chatham House.

Murphy, J.J., (1991). Intremarket Technical Analysis, Trading strategies for global stock, bond, commodity and currency markets. New York, NY, USA: Wiley-Finance Editions. ISBN: 0-471-52433-6

Pecht, M. (2008). Prognostics and Health Management of Electronics. New York, NY, USA: Wiley-Interscience.

Pecht, M. (2010). A Prognostics and Health Management Roadmap for Information and Electronics-Rich Systems. *IEICE ESS Fundamentals Review, 3*(4), 425-432.

Reim, W., Parida, V., & Ortqvist, D. (2015). ProducteService Systems (PSS) business models and tactics e a systematic literature review. *Journal of Cleaner Production, 97*, 61-75. doi: http://dx.doi.org/10.1016/j.jclepro.2014.07.003

Sun, B., Zeng, S., Kang, R., & Pecht, M. (2010). Benefits Analysis of Prognostics in Systems. Macau: *Prognostics & System Health Management Conference.*

Sandborn, P. A., & Wilkinson, C. (2007). A maintenance planning and business case development model for the application of prognostics and health management (PHM) to electronic systems. *Microelectronics Reliability*, vol. 47, no. 12, pp. 1889-1901.

Tahan, M., Tsoutsanis, E., Masdi, M., & Abdul Karim, Z. (2017, April 15). Performance-based health monitoring, diagnostics and prognostics for condition-based maintenance of gas turbines: A review. *Applied Energy, 198*, 122-144. doi:http://dx.doi.org/10.1016/j.apenergy.2017.04.048

Wang, W., & Pecht, M. (2011, July). Economic Analysis of Canary-Based Prognostics and Health Management. *IEEE Transactions On Industrial Electronics, 58*(7), 3077-3089. Retrieved June 2020

Xu, P., Wang, Z., & Li, Y. (2010). Prognostics and Health Management (PHM) System Requirements and Validation. Macau.

Yang, M., & Blyth, W. (2007). *Modeling Investment Risks and Uncertainties with Real Options*. Retrieved July 14, 2020, from http://www.iea.org/w/bookshop/add.aspx?id=305

Zio, E. (2016, December). Some Challenges and Opportunities in Reliability Engineering. *IEEE Transactions On Reliability, 65*(4), 1769-1782. Retrieved June 15, 2020

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APPENDIX

Table A1: Characterization of probability distributions of Input Data for Monte Carlo Simulation

INPUT	DISTRIBUTION	MEAN/MIN	STD/MAX
Oil Price	Normal	\$45.00	\$1.00
Gas Price	Normal	\$2.50	\$0.05
Discount Rate	Uniform	4.00%	7.00%

Table A2: Downtime input cost data for FinPHM

Mean time to repair (hrs.)	23
Mean time to replace (hrs.)	60
Repair supporting material cost	9,800
PMV material cost	9,800
Scheduled repair indirect support	2,000
Unscheduled repair indirect support	3,000
Scheduled replacement indirect support	6,000
Unscheduled replacement indirect support	7,000
Cost of manpower for scheduled maintenance (\$/hr)	35
Cost of manpower for unscheduled maintenance (\$/hr)	50

Table A3: Downtime for Maintenance Approaches

System	CBM Approach		Run to Failure	
Maintenance	Repair	Replace	Repair	Replace
Downtime (hrs)	73	132	167	228

Table A4: Production and Market Data

Gas selling price (\$/scf)	2.5
Oil selling price (\$/bbl)	45
Project Discount Rate (%)	5
Average Oil Production (000 bbls/day)	83.21
Average Gas Production (000 scf/day)	44.53
Oil Tariff rate at Base Year (\$ Million)	0.6
Gas Tariff rate at Base Year (\$ Million)	0.4
Field Life (yrs)	37

Table A5: Simulation Results

System Performance (%)	Failure Distribution	Nature of Distribution	K-Factor (%)	Maintenance Savings (\$M)	Average Change in NPV (%)	Average Change in PIR (%)	OEM NPV (\$M)
91.49	Weibull	SF <1	75.11	1.0762	50.23	14.41	28.47
53.91	Weibull	SF <1	4.73	1.0762	-80.49	-89.23	11.6
86.06	Weibull	SF =1	0.23	0.114	-83.51	-92.63	7.77
86.89	Normal	$\mu_v = \mu$	0.78	0.043	-11.61	-84.52	24.93
79.22	Normal	$\mu_v \gg \mu$	35.88	0.9024	13.41	-5.44	22.84
79.58	Normal	$\mu_v \ll \mu$	0.89	0.0209	-37.24	-51.07	21.9

Figure A1: Interface of FinPHM Application developed using MATLAB