Cost benefit analysis of applying PHM for Subsea Applications

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ABSTRACT

The decrease in oil price has been a hot topic over recent years and has directly affected oil companies and original equipment manufacturers (OEMs) of systems used for oil production (subsea assets in particular). Numerous technologies, methodologies, processes and tools are being developed to support lifecycle cost reductions for subsea assets and to maximize the overall profits for the industry. Prognostic and Health Management (PHM) is a technology that can assess and predict the remaining useful life (RUL) of a system, enabling operations and maintenance strategies to be better planned. One goal of PHM is to lower the cost for a system during the operational period by reducing the downtime cost and risk of unanticipated failures. Traditionally, failure was accepted in this industry sector through the incorporation of functional safety features of critical components. Unfortunately, a fail-safe strategy has significant downtime costs associated with it. However, introduction of new technology (e.g. PHM) requires a business case to demonstrate the potential benefits. At present there is a lack of literature on the topic of PHM cost-benefit-risk analysis for subsea production systems. This paper will provide a background of lifecycle cost and the potential cost savings PHM can deliver in the subsea application will be provided. The paper will also expand on four categories of factors contributing to the cost benefit analysis as well as a case study to illustrate the potential cost savings and the side-effects from PHM integration on subsea equipment.

1. INTRODUCTION

Oil and gas is the main source of energy in the world, but its value has dropped dramatically in last five years. From the Oil Company or OEM perspective, a higher oil market pricing combined with a lower associated lifetime cost has the potential to produce higher profits. However, in earlier subsea projects, strategies for maintaining the platform infrastructure were produced as an afterthought (Moreno-Trejo & Markeset, 2011). One of the major financial challenges for the oil and gas industry is the extensive intervention and repair costs during the field lifecycle. Furthermore, shallow-water opportunities are becoming limited and the development of deep water reserves are expected to accelerate into the future (Ivanova & Brkic, 2015). When subsea systems move into deeper water, cost of the production stage is significantly increased. Operators are trying to improve the operational reliability on their assets in order to reduce the maintenance and operational costs. The PHM capability is used to predict the condition of the system into the future, thus enabling the remaining useful life (RUL) calculations to be determined for each component in a system. This enables opportunistic maintenance actions to be embedded into the planned maintenance campaigns as well as optimization of maintenance strategies. A lot of these analyses are starting to be offered by subsea OEMs to the operators as services, and PHM might act as an enabler for product-service-subsea systems, a new paradigm already adopted by other industry sectors (Baines, Lightfoot, Evans, Neely, Greenough, Peppard, Roy, Shehab, Braganzam, Tiwari, Alcock, Angus, Bastl, Cousens, Irving, Johnson, Kingston, Lockett, Martinez, Micheli, Tranfield, Walton, & Wilson, 2007). This paper discusses the construction of cost-benefit analysis supporting the adopting of PHM and aims to quantify its benefits during the operation on subsea applications. The paper provides a brief background of SPS's lifecycle cost and the impact the PHM might have within the business. The major body of this paper will be delivered in three sections. First section discusses the PHM development costs associated with the realization of PHM, the technologies and related support elements to apply PHM into SPS. The cost-benefit analysis is used to quantify the savings when a PHM system is applied to a SPS over a specific operational period. In the second section, four factors that affect the cost associated with PHM subsea application are analyzed. Finally, a case study of using PHM on subsea control valves for subsea X-mas tree will be run through the cost-benefit-risk analysis.

2. SPS LIFECYCLE COST ANALYSIS

The lifecycle cost of a subsea production system (SPS) is the sum of capital expenditure (CAPEX), operation expenditures (OPEX), reliability, availability and maintainability expenditures (RAMEX) and risk expenditures (RISKEX) (Bai & Bai, 2012). Briefly, these expenditure costs are covered below.

- CAPEX: the costs for all material and installation of subsea system
- OPEX: operating costs to perform well intervention and work overs
- RAMEX: the sum of cost of production lost and cost of repair /replace associated with component failures
- RISKEX: the loss of well control (blowouts) during drilling, completion, production, work overs, and re-completions

Very often, the lifecycle cost of a subsea project is discussed from a CAPEX and OPEX perspective as RAMEX and RISKEX are typically counted as part of the OPEX. However, a joint industry project (JIP) analyzed these four types of expenditures for two types of subsea systems configuration (conventional trees (CTX), and horizontal trees (HTX)), for four and six subsea wells at water depths of 4000 and 6000 feet respectively, over a 10-year period. Figure 1 highlights an estimate of lifecycle cost for the eight cases of subsea field development (with CAPEX, OPEX, RISKEX, and RAMEX contributions) (Goldsmith & Ericson, 2000). The results clearly show that CAPEX and RAMEX are two major costs in the 10 years period under investigation. From the analyzed data, the cost of CAPEX and RAMEX for the subsea X-mas tree is roughly 92% of the overall lifecycle cost. Since the cost of the SPS is fixed, the only cost operators can tackle is the one involving the RAMEX. PHM is one of the methods that could reduce maintenance cost and improve availability of a subsea system.

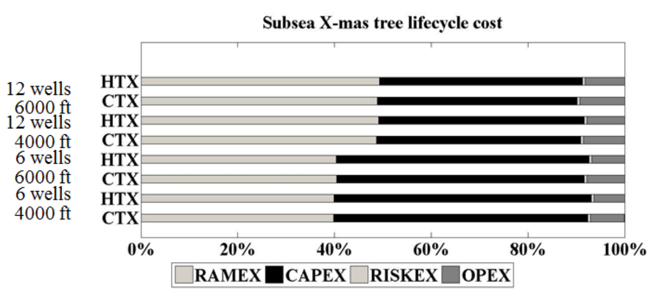


Figure 1. Results for subsea X-mas tree life cycle cost (Goldsmith & Ericson, 2000)

3. COST OF PHM IMPLEMENTATION

If PHM is introduced into a subsea system design, both the OEM and the operator must be responsible for the implementation of this capability (He et al., 2011). The SPS OEM drives the development and integration PHM echnology although both parties must deploy R&D efforts to gain the knowledge of system's behavior under healthy and faulty conditions. This process usually requires significant time and effort and it can also be very expensive (Sandborn, 2009). The PHM implementation is developed by a multi-disciplinary functional team by using engineering data from a variety of sources of knowledge. The functional team consists of employees from subsea equipment design, reliability engineering, maintenance, logistics, operators, regulators, etc.. The cost parameters of PHM implementation are divided into six sectors: labor, technical point, PHM supporting data/information, manufacturing site, logistic, and marketing, see Table 1 (Sandborn, 2009)(Feldman, Sandborn, & Jazouli, 2008) (He, Zhao,& Xu, 2011). The labor costs include all related disciplines which are able to contribute and support the PHM system for subsea application. Mostly wages, travel, accommodation and welfare are included in the labor cost. From the technical point, all costs are related to the facilities which may involve third-parties or suppliers will be used to investigate the subsea application installed with PHM system. To capture historical data from field experience, expert judgment and testing represents one of the main challenges during the PHM design and implementation. The data is used to identify the critical components and plan the maintenance for these components through reliability and maintainability engineering analysis. Logistic costs cover the costs running the PHM design and development project, such as rent fee for the workplace, laboratory and related place which are required for investigations, the energy cost and media cost. It also includes the transportation fee for the facilities which are needed for implementation and procurer to travel to negotiate with suppliers. In the end, before using PHM system in real applications, qualification from the classification society is required to judge the system meets standards. It also needs risk assessed for the operator to protect human life, environment, and production.

The cost models used in the subsequent sections are able to deliver a cost benefit analysis when all elements costs and length of the project are identified. Due to the unpredictability of PHM implementation, the total cost requires an additional 15% of development cost.

Functional Factors	**Influencing factors**
Labor	
Wages and related costs	Project managers
	Operators
	Reliability engineer
	Maintenance engineer
	Subsea designer
	Logistical staff
Technical point	
Subsea equipment cost	Subsea manufactures
Software design cost	IT engineer

Instrumentation cost	Instrumentation supplier
Testing & prototype costs	Subsea manufactures
Integration cost	Subsea manufactures
Re-conditioning cost	Subsea manufactures
Qualification cost	Subsea manufactures
Supporting data	
Cost of data archiving	Failure history
	Past operation condition
	Maintenance history
Manufacturing	
Additional processing	Subsea manufactures
Additional hardware	Subsea manufactures
Installation cost	Subsea manufactures
Logistic cost	
Rent and utility cost	Workplace
	Laboratory
Transportation fee	Business
	Facility
	Investigate or survey
Training cost	Employee
Route to Market	
Cost of risk assessment	Risk manager
Qualification	Classification society

Table 1. The cost parameters for PHM implementation.

4. FACTORS INFLUENCING LIFECYCLE COST OF ADOPTING PHM ON SPS

Past works have highlighted the cost-benefit analysis for implementation of the PHM capability on aerospace applications (Leao, Fitzgibbon, & Puttini, 2008) (Kahlert, Giljohann, & Klingauf, 2014). These show that adopting PHM within a system can lead an overall cost saving during the operational time. PHM can reduce/avoid unnecessary four cost factors during the operational time which will be presented in the following sections.

4.1. Repair Costs

Previous research demonstrated that PHM is able to reduce the number of corrective and time-based maintenance actions and instead it allows operators to conduct scheduled and opportunistic maintenance. PHM is also able to avoid the number of unnecessary repair activity, thus reduce the total repair cost. The number of the spare parts, tools and equipment, and man power and man hours will also be reduced as a result of a better understanding of the current state of health of the system. The following formulas describe the cost of scheduled repair and unscheduled repair for an asset.

$$C_1 = C_{ms} \times h + C_{\mathrm{d}} \times D + S_{sm} \qquad (1)$$

$$\mathrm{C}_2 = C_{mu} \times h + C_{\mathrm{d}} \times D + S_{um} \qquad (2)$$

At a system level, the total cost from scheduled repair and unscheduled repair are calculated as follows:

$$C_{1system} = \sum_{i=1}^{N_{C1}} (n_i \times \mathrm{C}_1) \qquad (3)$$

$$C_{2system} = \sum_{j=1}^{N_{C2}} (n_j \times \mathrm{C}_2) \qquad (4)$$

4.2. Replacement costs

Failure rates in an SPS follow the traditional bathtub curve, illustrated in Figure 2 (Strutt &Wells, 2014). This shows a larger number of failures occurring early on in the lifecycle. During the useful life phase, the failure rate becomes random due to the condition of system not being controlled. PHM technology is based on the knowledge from reliability engineering. From a reliability perspective, this shows how the reliability of a system is connected with the assets age. The final goal of subsea OEMs is to improve the reliability in the early life phase to same level with useful life phase; processes and procedures to support the reduction of the high failure rates in the early life phase are still in the development stage (Strutt &Wells, 2014) and existent recommended practices are not widely adopted by the subsea community.

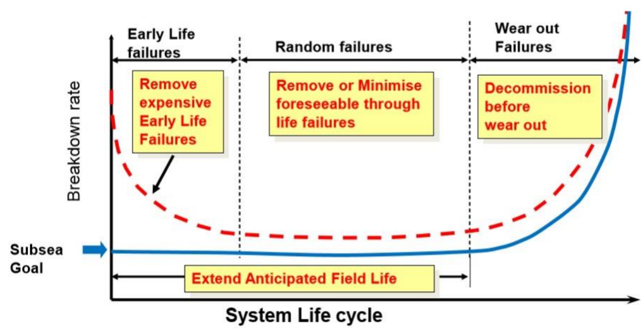


Figure 2. A perspective of the reliability bathtub curve for subsea application (Strutt &Wells, 2014).

However, during the wear-out phase, the product's age/wear makes likelihood of failure more uncontrollable. PHM technology is able to predict failures, however when a component is within the wear out phase, its failure likelihood will be higher, thus maintenance activity may not be worthwhile. Scheduling the replacement for a component at end of its useful life can reduced the total RAMEX. The following equations show the cost of replacement for a component with and without the PHM capability:

$$\mathrm{C}_3 = C_{ms} \times h + \mathrm{C}_r + C_{\mathrm{d}} \times D + S_{sr} \tag{5}$$

$$\mathrm{C}_4 = C_{mu} \times h + \mathrm{C}_r + C_{\mathrm{d}} \times D + S_{ur} \tag{6}$$

4.3. Downtime costs

The PHM capability also plays a key role in reducing system's downtime. Operating the system with PHM provides operators with advanced warning of potential failures, thus maintenance can be scheduled and breakdown time and production loss can be reduced. PHM increases equipment availability, lowers the time of maintenance and maximize the asset availability through its lifetime. The downtime cost (RAMEX) for repair and replacement, with and without PHM for each component, and lost production cost are calculated as follows:

$$C_P(t) = T \times W \times O \tag{7}$$

$$\mathrm{C}_5 = \mathrm{C}_1 + C_P \tag{8}$$

$$\mathrm{C}_6 = \mathrm{C}_2 + C_P \tag{9}$$

$$\mathrm{C}_7 = \mathrm{C}_3 + C_P \tag{10}$$

$$\mathrm{C}_8 = \mathrm{C}_4 + C_P \tag{11}$$

At a system level, the total cost associated with downtime cost is total downtime cost with PHM and total downtime cost without PHM calculated as:

$$RAMEX = \sum_{i=1}^{N_{C1}} (n_i \times \mathrm{C}_5) + \sum_{I=1}^{N_{C2}} (n_I \times \mathrm{C}_5) + \sum_{j=1}^{N_{C3}} (n_j \times \mathrm{C}_7) \sum_{J=1}^{N_{C4}} (n_J \times \mathrm{C}_8) \tag{12}$$

4.4. Operational safety risks

Typically, in the SPS industry, failure can incur uncontrolled leaks which will incur expense and consequential damage for asset and environment - such as pollution, lost production, diversion of planned maintenance resources as well as loss of company reputation (Brown & Sondalini, 2015). A PHM capability can help in making a decision to preform planned maintenance actions ahead, thus reducing fault occurrence and consequential damage from a fault. When PHM is applied to a SPS, the cost of risk (RISKEX) is calculated as follows:

$$\mathrm{C}_7 = P_d \times C_b \tag{13}$$

Mannan (2014) reported on the cost of subsea failures (blowouts) in the oil and gas industry throughout the world and these are summarized in Table 2.

Area	Date	Value (\$M)	Current Value (\$M)
Fateh L3, Dubai, UAE	07/01/1975	79	340
Gulf of Mexico US	11/04/1987	200	440
Enchova, Campos Basin, Brasil	04/24/1988	330	700
Treasure Saga, North Sea, UK	01/20/1989	220	460
Mediterranean, Egypt	08/10/2004	190	260
Montara, Timor Sea, Australia	08/21/2009	250	280
Gulf of Mexico US	04/21/2010	560	560
Gulf of Mexico, Louisiana, US	07/23/2013	140	140

Table 2. Cost of blowout.

5. A CASE STUDY FOR THE COST-BENEFIT ANALYSIS

In this paper we propose the example of a PHM capability added to a subsea X-mas tree to articulate the cost benefit analysis supporting the case for PHM on control valves of such subsea equipment. The lifecycle costs of SPS standard design will be compared to the one incurred by a PHM enabled SPS design (where the control valves are monitored). It is assumed that the SPS under investigation has five subsea x-mas trees, and each subsea x-mas tree includes two major control valves (the production master valve (PMV) and the down hole valve (DHV)). These control valves are critical to the operation. The comparison will highlight the effect of different levels of PHM system coverage. The percentage of PHM coverage for all control valves at system level will be evaluated from 0% to 100% in 10% increments. i.e. When there is Y% PHM enabled design, the SPS standard design of all valves is (100-Y) %. The concepts of calculation were adapted from study published for a scenario capturing the adoption of PHM for machine tools (Grubic, Jennions & Baines, 2009) and have been designed to show the costs, profits and benefits between standard design and PHM design.

Reliability data for the control valves under investigation was gathered from the 'Offshore Reliability Database' (OREDA, 2015) and they summarized in Table 3. Table 3 provides the average data collected from several operators in over a number of years which is required for calculating the cost for SPS standard design and SPS PHM enable design for a subsea control valves. OREDA compiles real offshore equipment reliability data collected from world-wide oil and gas operations of assets currently in service and used in the oil and gas industry. It compiles failure rate and repair time information from several operators (BP, ConocoPhillips Scandinavia AS, Eni S.p.A Exploration & Production

Division, ExxonMobil Production Company, Gassco, Shell Global Solutions, Statoil Total S.A.). The reliability database specifies that 97% of failure modes for control valves are classified as critical. Critical failures are defined as a failure which causes immediate and complete loss of an equipment unit's capability of providing its output.

Control valves	
Operation hours	39010
Critical failure	41
Active repairs time (hrs.) (MTTR)	23

Table 3. OREDA data related to control valves in a subsea X-mas tree.

Unfortunately, it is impossible for authors to collect the historical data on SPS performance, due to this data being confidential and restricted to the public. The data captured in Table 4 represents discreet values from field experience and several publications (Goldsmit & Ericson, 2003) (Mamman, Andrawus, & Lyalla, 2009).

Input Data	**Input**
Operation time (hrs.)	39,010
No of failures	41
% of valves with the PHM capability	From 0% to 100%
Number of Subsystem Removals	1
Mean time to repair (hrs.)	23
Mean time to replace (hrs.)	60
DSV Hire Cost ($/per day)	$30,000
MSV Hire Cost ($/per day)	$60,000
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)	$30
Cost of manpower for unscheduled maintenance ($/hr)	$40
Well production rate (barrels of oil per hour)	$416
Oil selling price	$10

Table 4. Input data for the cost benefit analysis tool.

Using Eq. (1) and Eq. (2), the cost of scheduled repair and unscheduled repair for each control valve is $62,687 and $63,916, respectively. The total cost from both repair approaches account for the total number of failures which are anticipated or not. With PHM support, before failure occurred in each valve, repair activity will be planned. To analyses the cost saving of using PHM, the percentage of control valves with PHM is set from 0% to 100% with increments of 10%. Assuming all control valves are covered by the PHM system, 41*10*100% failure could be predicted and 41*10*(1-100%) failure will occur without prediction during the operation hours. According to Eq. (3) and Eq. (4), the total cost for both repair are as follows:

$$C_{1system} = \$62{,}687 * 410 * \ \% \text{ of valve with PHM}$$

$$C_{2system} = \$63{,}687 * 410 * (1 - \ \% \text{ PHM coverage})$$

Using Eq. (5) and Eq. (6) the cost of scheduled replacement and unscheduled replacement are $197,600 and $199,200 respectively. In this case study, the number of valve removals was assumed as one during the operation time for each valve.

Mean time to repair (MTTR) in the Table 2 is one part of the downtime. Generally, mean down time (MDT) includes repair time, shutdown time, start-up time, preparation time (PT) such planning maintenance activity, waiting times for parts, logistics or supplier delays, etc (Robert & Liang , 2002). Figure 3 shows the MDT differences between the control valves without and with the PHM capability.

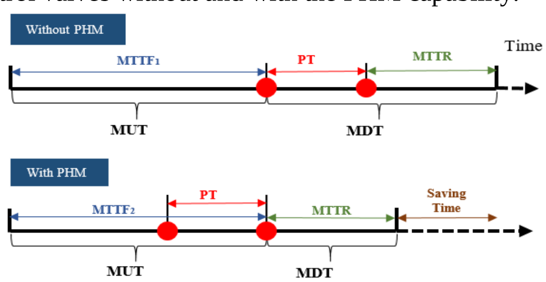


Figure 3. MDT between without PHM and with PHM.

Table 5 lists MDT and according to Eq. (7), lost production cost for the repair and replacement with and without PHM are presented:

	Without PHM		With PHM	
	Repair	Replace	Repair	Replace
MTTR	23	60	23	60
Waiting DSV or MSV	2 days	3 days	0	0
Mobilizing DSV or MSV	24	24	0	0
Demobilizing DSV or MSV	24	24	2	24
Shutdown	24	24	24	24
Start up	24	24	24	24
Total hours	167	228	95	132
Lost Production Cost	$555000	$758000	$315000	$439000

Table 5. The MDT and Production Lost.

When a SPS is supported by PHM, the MDT could be reduced as the preparation time could be avoided. The results from Eq. (8) to Eq. (11); cost savings between scheduled and unscheduled activity and summary of maintenance and lost production cost are presented in the Table 6. All result about cost of 0% to 100% PHM enabled design of control valves are listed in the Appendix.

	Maintenance Cost	Lose production cost	Downtime cost
Scheduled repair	\$62,687	\$315,827	\$378,514
Unscheduled repair	\$63,916	\$555,443	\$619,359
Saving for repair	\$1,229	\$239,616	\$240,845
Scheduled replacement	\$197,600	\$439,296	\$636,896
Unscheduled replacement	\$199,200	\$758,784	\$957,984
Saving for replacement	\$1,600	\$319,488	\$321,088

Table 6. The summery of maintenance cost and lost production cost.

6. DISCUSSION

The case study covered in the previous section highlights the results of the cost-benefit analysis for the adoption of PHM on a subsea X-mas tree. The results show that when preparation is conducted prior to maintenance, the total system's MDT and avoidable cost of unscheduled activities are reduced. Figure 4 illustrates the total activity cost savings, including production lost and the total RAMEX at a system level for repair and replacements, for different levels of PHM implementations. The number of interventions for repair and replacement did not reduced, however the 99% of RAMEX saving came from the lost production savings. Comparing with the cost of scheduled and unscheduled activity in the table 6, the reduction in lost production cost for a PHM enabled SPS design is \$239,616 and \$319,488 for a repair activity and a replacement activity, respectively. However, a PHM enabled SPS design for a repair activity and a replacement activity is only reduced by \$1229 and \$1600. A 100% PHM enabled SPS design offers a system estimated potential total savings of \$101.96M. Each 10% increase in PHM enabled SPS design transforms into a \$10.2M in savings. However, compared with the potential of cost reduction from production loss, repair and replacement cost savings can be neglected. Thus, the cost of production lost is an avoidable cost and occupied the main cost of the downtime cost, so there is a potential to save the total life cycle cost during the operation time.

In this case study, estimates on costs related to maintenance and production lost are easy to calculate if the data and information from previous projects is accessible. However, there are a lack of data and cost information to support life cycle cost which need be acquired from maintenance activity, operation databases and experiences.

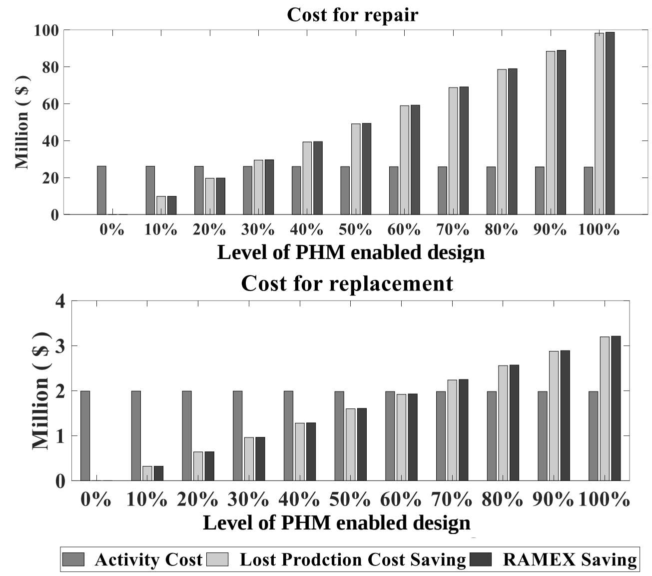


Figure 4. Costs of repair and replacement activity.

7. The side effect of a PHM enabled SPS design

PHM technology is also prone to failure because its behaviors are still not fully developed/ understood, so it can't make an accurate prognosis every time a failure is going to occur, which results in either a false positive or a false negative. A false positive (also known as a false alarm) is when equipment is in good condition which leads to maintenance being conducted when not required. A false positive is an over optimistic prediction which results in running a failure. Inaccurate PHM outcome will add to the total RAMEX costs and reduce the total cost saving. A false positive will reduce the availability of the system and west component useful life. The consequent cost for a false positive will depend on the time of occurrence during the MTTF. If this occurs at earlier stage of MTTF, the consequent cost is the same to carry out unscheduled maintenance, resulting in shut down of the system for no purpose. If a false positive occurs at the late stage of MTTF, meaning if a PHM enabled SPS design is applied the result is the same as a SPS standard design, thus the consequent cost is same value as the cost saving from a PHM enabled SPS design. The range of consequent cost for a false positive is listed in Table 7. A false negative will change the expectation of scheduled activities to the original corrective maintenance strategy. Thus, a false positive outcome has the same value as the cost saving from SPS with PHM, listed at Table 7. A side-effect of the PHM capability may be increased numbers of maintenance activities during the operational life time of an asset. For critical components, SPS cannot afford to run to failure, thus accepting slightly pessimistic false negatives might be required for safety reasons.

	False positive	False negative
Repair	$240,845- $378,514	$240,845
Replacement	$321,088- $636,896	$321,088

Table 7. The consequence cost of imperfectly performing PHM capability.

8. SIMULATION FOR AN IMPERFECTLY PERFORMING PHM CAPABILITY

In this section, a Monte Carlo simulation will be applied to determine the cost consequence of an inaccurate PHM outcome. Monte Carlo analysis allows evaluation of the performance of the system without knowing the actual system and enables performing "what if" analysis of proposed substitutes. The future state of the subsea production system is predicted based data gathered previously. The example which will be provided is the false negative for repair.

The assumed number of failures for a subsea control valve over the previous 10 years is shown in Table 8, and probability distribution based on the reliability bathtub curve for subsea application. Two scenarios are using Monte Carlo simulations.

The cost associated to the consequences of a false negative for the repair is set from $240,845- $ 378514. For scenario 1, the PHM system will improve when the system detects more faults and become more accurate, thus the cost of unexpected consequence will reduce during operation. For scenario 2, the performance of PHM system will degrade over the time, thus the cost of unexpected consequence will increase from low to high. The relationship between consequence cost for scenario 1 and scenario 2 and interval are a linear function and presented in Figure 5. The consequences cost for each interval are listed in Table 8.

No. of year	No. of Failure	Probability of failure	Interval	scenarios 1 ($)	scenarios 2($)
1	1	0.03	0 -2	240,845-378,514	240,845-244,975
2	1	0.03	3-5	240,845-374,384	240,845-249,105
3	2	0.04	6-9	240,845-370,254	240,845-254,612
4	2	0.05	10-14	240,845-364,747	240,845-261,495
5	3	0.06	15-20	240,845-357,864	240,845-269,755
6	3	0.07	21-27	240,845-349,604	240,845-279,392
7	3	0.09	28-36	240,845-339,967	240,845-291,783
8	6	0.14	37-50	240,845-327,576	240,845-311,056
9	8	0.2	51-70	240,845-308,303	240,845-338,589
10	12	0.29	71-99	240,845-280,769	240,845-378,514

Table 8. Data for Monte Carlo Simulation

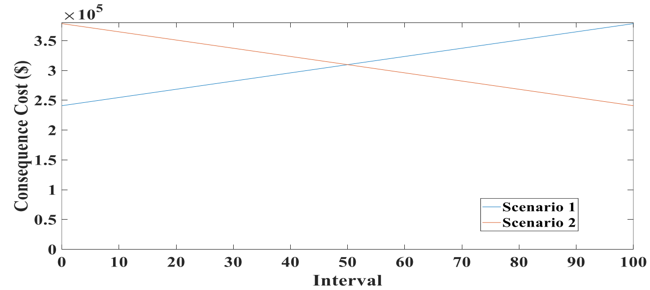


Figure 5. Liner function for Scenario 1 & 2

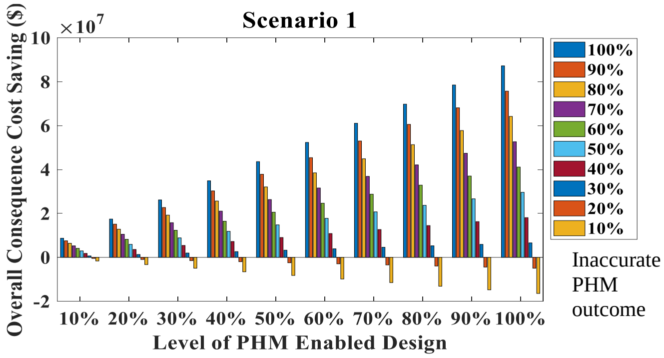
Using the data in Table 8, Monte Carlo simulation will evaluate the average total consequence cost of false negative for the system, from 10% to 100% PHM enabled SPS design with increments of 10%, when the false negative rates are also varying from 10% to 100%.

A 100% PHM enabled SPS design aims at detecting and isolating all 410 faults that might occur in service. The Monte Carlo simulation considered variation of false negative in step of 10% of the total number of failure. Using the probabilities stated and related consequence costs in Table 8, 1000 samples were taken and 41 random numbers were generated for each failure to provide divergence in the consequence cost. The risk needs to be consider when PHM is been applied. When the cost-benefit considers the total consequence cost of inaccurate PHM outcome, it will reduced linearly, following the level of PHM enabled and inaccuracy. Due to the cost-benefit analysis for risk varying also dependent on the environmental conditions, this is not covered in this paper. This case study of the overall cost saving shows in Figure 6.

Both of the two scenarios show when PHM inaccuracy is higher than 80%, each level of PHM enabled SPS design will increase CAPEX cost and not save any cost during operation (OPEX). However this Monte Carlo simulation assumed a range of parameters to be fixed (e.g. number of failures, operational time and consequence cost for each failure). If these parameters and investment costs where more dynamic, the PHM enabled SPS design would require accuracy greater than 40% over 5 years to break even. A future study will include different types of distributions for these parameters in a more comprehensive Monte Carlo simulation supporting the cost–benefit-risk analysis for the adoption of PHM on different subsea systems and field configurations.

9. CONCLUSIONS

The purpose of this paper was to consider the adoption of PHM capability for SPS applications and to analyze how PHM will affect the overall life cycle cost of a typical subsea production system. A review of the structure of lifecycle costs for a SPS and the potential cost savings that can be ascertained during a SPS's lifetime have been provided.



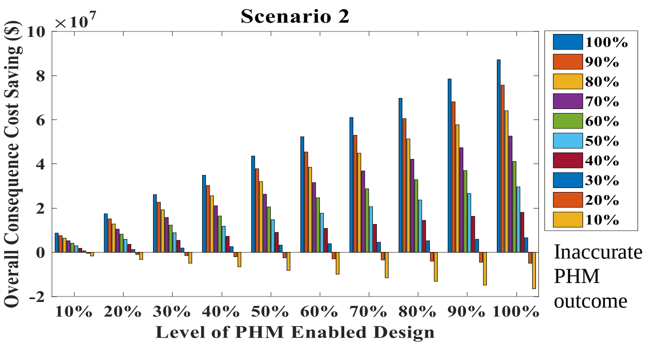


Figure 6: Total cost saving.

Furthermore, a case study covering the estimated cost savings for PHM introduction on a set of X-max tree control valves was given. PHM can play an important part for SPS's life time cost in the future and the case study has demonstrated the potential cost saving of using PHM technology in the oil and gas industry. However, further research is required to build an understanding of the full benefits of PHM at a system level and the requirements to be considered during the design stage of a SPS. This knowledge and data would enable a more accurate cost benefits analysis which would aid operators and manufacturers in decision making when considering PHM implementation as part of the subsea design.

NOMENCLATURE

C_1: cost of scheduled repair for each component
C_2 :cost of unscheduled repair for each component
$C_{1system}$:total cost for scheduled repair
$C_{2system}$:total cost for unscheduled repair
C_3 : cost of scheduled replacement for each component
C_4 :cost of unscheduled replacement for each component
C_5 :downtime cost for scheduled repair without PHM
C_6 :downtime cost for unscheduled repair with PHM
C_7 :downtime cost for scheduled replacement without PHM
C_8 :downtime cost for unscheduled replacement with PHM
C_9 : total downtime cost (RISEX)
C_b :cost of damage (blowout)
C_d :cost per day for diving support
C_r :cost of repairing components
C_{ms} :cost of manpower for scheduled activity
C_{mu} :cost of manpower for unscheduled activity
C_P :cost of lost production
D :days for hiring diving support equipment
h :man- hours
N_{C1} :number of components with PHM applied
N_{C2} :number of components without PHM applied
O :oil selling produce
P_d : probability of blowout during lifetime
S_{sr} :scheduled replacement (indirect support)
S_{ur} :unscheduled replacement (indirect support)
S_{um} :unscheduled repair (indirect support)
S_{sm} : scheduled repair (indirect support)
T :downtime (MDT)
W: well production per day

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BIOGRAPHIES

Xiaojing Gao is a 3rd Year PhD Student at Glasgow Caledonian University. She received her MSc in Mechanical engineer at Glasgow Caledonian University in 2015. Her research project covers the design and development of health ready subsea production systems and their through-life support solutions. Her research interests include PHM technology, integrity management, lifetime cycle and reliability analysis, and maintenance activities for subsea production systems.

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Don McGlinchey graduated from Strathclyde University with a BSc (Hons) Physics before working as a project engineer at Babcock Energy Ltd. He returned to academia and gained an MSc in Bulk Solids Handling Technology and his Doctorate on a study of the effect of vibration on powder beds. He is currently a Professor in the Department of Engineering at Glasgow Caledonian University where he is the academic leader in teaching, research and consultancy in the area of multi-phase flow. He has edited two books, and authored over 100 papers, articles and consultancy reports.

APPENDIX

% of Valve with PHM	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
The number of valves with PHM	0	1	2	3	4	5	6	7	8	9	10
The number of valves without PHM	10	9	8	7	6	5	4	3	2	1	0
Total number of Failure	410	410	410	410	410	410	410	410	410	410	410
Number of activities											
Total number of scheduled repair	0	41	82	123	164	205	246	287	328	369	410
Total number of unscheduled repair	410	369	328	287	246	205	164	123	82	41	0
Total number of scheduled repair	0	1	2	3	4	5	6	7	8	9	10
Total number of unscheduled repair	10	9	8	7	6	5	4	3	2	1	0
Cost ($M)											
Scheduled repair	0	2.57	5.14	7.71	10.28	12.85	15.42	17.99	20.56	23.13	25.70
Unscheduled repair	26.21	23.59	20.96	18.34	15.72	13.10	10.48	7.86	5.24	2.62	0
Scheduled replacement	0.00	0.20	0.40	0.59	0.79	0.99	1.19	1.38	1.58	1.78	1.98
Unscheduled replacement	1.99	1.79	1.59	1.39	1.20	1.00	0.80	0.60	0.40	0.20	0.00
Total repair cost	26.21	26.16	26.10	26.05	26.00	25.95	25.90	25.85	25.80	25.75	25.70
Total replacement cost	1.99	1.99	1.99	1.99	1.99	1.98	1.98	1.98	1.98	1.98	1.98
Total maintenance cost	28.20	28.15	28.09	28.04	27.99	27.94	27.89	27.83	27.78	27.73	27.68
Production lost ($M)											
Scheduled repair	0	12.95	25.90	38.85	51.80	64.74	77.69	90.64	103.59	116.54	129.49
Unscheduled repair	227.73	204.96	182.19	159.41	136.64	113.87	91.09	68.32	45.55	22.77	0
Scheduled replacement	0.00	0.44	0.88	1.32	1.76	2.20	2.64	3.08	3.51	3.95	4.39
Unscheduled replacement	7.59	6.83	6.07	5.31	4.55	3.79	3.04	2.28	1.52	0.76	0.00
Total production lost	235.32	225.18	215.03	204.89	194.74	184.60	174.46	164.31	154.17	144.03	133.88
Saving ($M)											
Repair activity saving	0	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50
Replacement activity saving	0.000	0.002	0.003	0.005	0.006	0.008	0.010	0.011	0.013	0.014	0.016
Total maintenance saving	0	0.05	0.10	0.16	0.21	0.26	0.31	0.36	0.42	0.47	0.52
Total production lost for repair saving	0.00	9.82	19.65	29.47	39.30	49.12	58.95	68.77	78.59	88.42	98.24
Total production lost for replacement saving	0.00	0.32	0.64	0.96	1.28	1.60	1.92	2.24	2.56	2.88	3.19
Total production lost saving	0.00	10.14	20.29	30.43	40.57	50.72	60.86	71.01	81.15	91.29	101.44
Total repair cost saving	0.00	9.87	19.75	29.62	39.50	49.37	59.25	69.12	79.00	88.87	98.75
Total replacement cost saving	0.00	0.32	0.64	0.96	1.28	1.61	1.93	2.25	2.57	2.89	3.21
Total cost	263.52	253.32	243.13	232.93	222.73	212.54	202.34	192.15	181.95	171.76	161.56
Total Saving	0	10.20	20.39	30.59	40.78	50.98	61.17	71.37	81.57	91.76	101.96