Journal of Petroleum Science and Engineering 205 (2021) 108890

Contents lists available at ScienceDirect

Journal of Petroleum Science and Engineering

journal homepage: www.elsevier.com/locate/petrol

CBM challenges and opportunities for O&M of the Johan Sverdrup Oil and Gas Field

Jose V. Taboada[a], Vicente Diaz-Casas[a,*], Xi Yu[b]

[a] Integrated Group for Engineering Research, CITIC (Centre for Information and Communications Technology Research), University of A Coruña (UDC) – Campus do Mar, C/ Mendizabal, 15403, Ferrol, A Coruña, Spain
[b] Wind Energy Specialist and International Project Manager, China Energy Engineering Corporation (University of Strathclyde), R3.36, Royal College Building, 204 George Street, Glasgow, G1 1XW, UK

ARTICLE INFO

Keywords:
Phases of johan sverdrup
Concept selection
Production profiles
Oil&Gas price
Condition base monitoring (CBM)
O&M philosophy
Maintenance strategy
IO principles
LCC Analysis
O&M cost
Downtime cost
Cost-benefit analysis (CBA)
Cash-flow
And future outlook

ABSTRACT

Paper describes the challenges and forward developments to face up on Operation and Maintenance (O&M) issues at the Johan Sverdrup field (Blocks: PL 501, PL 265 and PL 502), on the phases (Concept and Design, Construction and Hook-up, Commissioning, Operations and Maintenance, and Recycling), and a research study of the Oil&Gas profitability. Estimated reserves are between 1.8 billion to 2.8 billion bbl, so assessing the total risk of the field development is crucial. Although, development is estimated to cost up to $31 billion, but the full life-cycle price tag, including operating costs through 2068, is around $58.33 billion.

The purpose of this paper is to demonstrate a conceptual methodology analysis framework, for understanding how analysis of cost and benefits, are carry out for assessment and implementation of the Condition Base Monitoring (CBM) and measure the total OPEX (Operate Expenditure/Operating Cost). As well as a specific maintenance philosophy and conceptual approach on the business cases studies of the project lead, to a cost-effective solution. Paper begins by providing a background for analyzing the life-cycle impacts during the life of the field (50 years), and describing measures to implement during the O&M strategies. Follows by targeting the expectations, which one rest on profitability and optimization of the field, with oil prices above $60 per barrel (proved on Case 3). The harvest will, therefore, be profitable even after the price crash.

Life Cycle Cost (LCC) analysis (Alternatives A and B) focuses and identifies “Cost Items” (Cost Drivers) that the project carries. Achieved a reliable “concept development” is the greatest ambition, but uncertainties on Maintenance strategies and programs, have showed high cost at early phases. The aim was to measure the actual costs against predicted LCC and to calculate the cumulative costs throughout a product’s Life Cycle (LC) of the assets. Discussed and summarized the extent to which these costs and benefits may already take into account and how the CBM strategy mechanism should be works based on a model built.

Finally, is demonstrated through calculating an ″downtime scenario″ that could happens, which one creates Deferred Production Costs. Also, has been estimate the cost-benefit analysis (CBA) might be applicable on the researched project development ratio (cost vs. benefit), with overall maintenance effectiveness strategy under study on the LCC Alternative 2.

Therefore, describing the maintenance support functionality, based on input obtained from CBM systems and a predictive, periodic maintenance plan is indispensable, in order to cut off potential costs, target future benefits and guaranty a safety robust production installation. At the end, the paper addresses the future performance outlook development in the Oil&Gas Industry as whole, stating essential optimization valuable principles.

1. Introduction

The Johan Sverdrup field is located on the North Sea, at 140 km off the coast of Stavanger (to the West) in the Norwegian North Sea. Discoveries were made in 2010, at 1.900 m is placed the reservoir target point depth, field reservoir is formed of lower Cretaceous/Jurassic age high porosity and permeability sandstones. Peak production is estimated to be over 500.000 Barrels/day.

* Corresponding author.
E-mail addresses: jose.taboada1@udc.es (J.V. Taboada), vicente.diaz.casas@udc.es (V. Diaz-Casas), x.yu@strath.ac.uk (X. Yu).

https://doi.org/10.1016/j.petrol.2021.108890
Received 16 February 2021; Received in revised form 14 April 2021; Accepted 23 April 2021
Available online 8 May 2021

Johan Sverdrup is a giant Oil&Gas field located on the Norwegian continental shelf (NCS) and will at peak contribution of 25% (approx.) of the entire Norwegian shelf production. Oil&Gas field estimations lifetime are 50 years, expecting to start up production by end of 2019, and with predictable plateau production (550.000–650.000 BOE/day).

The lay-out (figure) can be find into the technical report (O at the Johan Sverdrup, 2014) and technical details (see into Table 1).

However, the concept selection established requires power from shore in the first phase, which will reduce total CO_2 emissions form the Utsire High area by 60–70%. The field development infrastructure comprises in the first phase compromises (process platform, drilling platform, riser platform and living quarter), which ones has been designed so as to facilitate future development. The installations are built by steel jackets that are linked by bridges. Agreements between partners (Table 1) set an Oil&Gas field center overall of consisting by power supply from shore, and four installations. Besides that, the main plan (developed phases) settled is characterized by five main deadlines: DG1(October 2012), AP1(October 2013), DG2(February 12, 2014), DG3 (14.020.2015) and First Oil (Dec 2019).

The history and timeline of the field, goes as fellow:

- 2010 – Johan Sverdrup Oil field discovered made.
- 2012 – Successful Johan Sverdrup appraisal well drilled.
- 2013 – Further appraisals.
- 2013 – Front-end-engineering design work, as well as an Engineering services, procurement and management assistance option for the development's first phase.
- 2014 – Concept selection completed.
- 2015 – Approval grant of the Plan Development Operator.
- 2019(Q4) – Production Start Up.
- 2050 – Field Production Horizon.

As to the technical and cost challenges reports, the Oil&Gas field is the biggest North Sea find in decades, will produce more at its peak than earlier thought and initial development costs will be below forecasts. In addition, the reservoir presents low pressure, it will in all oil producing wells to be injected gas under pressure in the bottom of the well to increase the flow of oil ("Gas-Lift Injection").

Uncertainties in new technology will be applied to raise the average recovery factor in "full bloom fields" as this one, while contributing to smart solutions for this total new project. Also, the totaling over 70.000 tons topsides distributed drilling, processing, riser platforms and living quarters. The size itself is something Aker Solutions has characterized as a "huge challenge" (Eikje et al., 2020).

As functional "Objectives of the Design and Requirements" that this particular field has to meet beforehand, are listed below:

- **Established a field center:** The ambition goal, is to carry out a recovery factor of 70%(approx.) for entire Oil&Gasfield.
- **Power from continental shoreline:** During Phase I, supply power will be provided from the shoreline through a transformer unit on Kårstø distributing direct current to the rise platform, guarantying an estimated 80 MW. With updated on power requirements (To obtaining more than 90% of the overall CO_2 emissions).

Table 1
Key Data (O at the Johan Sverdrup, 2014).

Location: North Sea
Water Depth: 110m.
Reserves Estimates: around 1.8 billion and 2.9 billion Barrels of Oil Equivalent, of which approximately 95% oil and about 5% rich gas.
Plateau Production: 550,000–650,000 BOE (Barrels of oil equivalent)/day.
Reservoir Details: Oil quality is highly mobile with low viscosity. It has an API of 28° and has a low gas/oil ratio.

- **Export Solutions:** For the Oil, is transport to shore (Mongstad terminal) through dedicated pipelines. Although, for the Gas transportation through Statpipe line and then further, to the Kårstø processing plant.

The optimality of the concept selection carries a direct bearing on both (production rates and CAPEX (Capital Expenditure/Acquisition Cost) profiles), as well as the electrification cost from shore could imply CAPEX way above of the total CAPEX estimate of 11$/BOE.

1.1. Production profiles and quality of oil

The production rates profiles are classified and described according to the Plan Development Operator (O at the Johan Sverdrup, 2014). Following figure(Fig. 1) show preliminary, not risked production profiles respectively oil and gas. The profiles are based on wells shut down when the proportion water exceeds 95%. The production profiles, are showed below:

As we can observe above, production regularity estimates vary for the entire production chain for Johan Sverdrup Phase 1. The table below (Table 2) shows an overview of estimated of production regularity and their corresponding probability of lost production.

In 2019, 2020 the start-up of new plant sand any teething problems that are expected to have the greatest impact on the regularity. In years when shut down, will shut down have the greatest impact, without shut down and commissioning problem is expected that errors in manufacturing critical equipment at the field center will have the greatest impact on the regularity (Budgen, 1992).

1.2. Uncertainties on the market by the oil&gas price

Challenge market uncertainties, are coming from by the drastic Oil plummeted to a low price ($115 down to $45 per bbl), which one has their root causes on the three main factors:

- Output production by USA Shale Oil; Higher Supply Production that requires lower investments and expenditures.
- Softening Demand in Asia; Being Asia the World Largest Consumer of Oil&Gas.
- Saudi Arabia decided "not to cut production" to support prices; So, continuing to add cheap bbl's in the market, where also this Supply Production requires lower on-going expenditures.

Those three combinations stated above, has bitted hard the "Competition Production" in the Oil&Gas Industry(Aven, 2015).

Where this drastic drop in the Oil price, has created an impact on "CAPEX cuts" (due to High CAPEX Expenditure) in large, risky (hazard environment) and expensive projects (Oil Sands in Canada, LNG and Artic Offshore Areas) to be develop, by the Oil&Gas Operators Companies. Applying conservative strategies, as "delaying project development execution", in order to save up investments during time being of lower Oil price(Apeland and Aven, 2000).

By another side, there are many ways to define "risk", in general it can be defined as the chance of bad consequence (Aven and Zio, 2018). In the Offshore Wind Turbine (OWT) field, it is the potential probability of suffering hostile the consequences that is of interest. Risk analysis as such, is the application of methods and tools to determine such probabilities. Also, it is important to distinguish between the terms risk and hazard. Risk can be defined as the accidental of something happening that will have an impact upon objectives. A hazard is a source of potential harm or may be a source of risk. To identify hazards and risks, hazard and operability studies and failure mode and effect and criticality analysis, both of them are the most common methods (Florian and Dalsgaard Sørensen, 2017).

Risk management process into the OWTs, is in charge to assist in the any decision-making on maintenance activities. Where potential

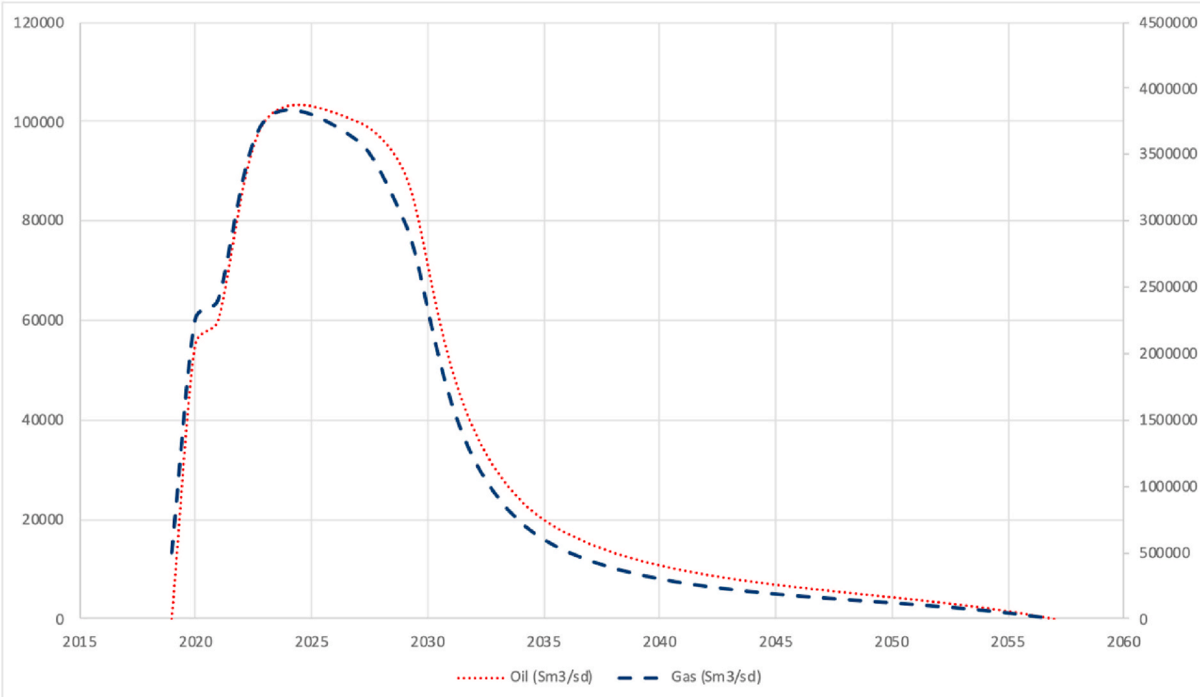

Fig. 1. Production profiles for Oil&Gas field development (O at the Johan Sverdrup, 2014).

Table 2
Estimated Production Regularity and Prob. of Production Lost.

Year	*2019*	*2020*	*2021*	*2022*	*2023–2027*	*2028*	*2029*
Prod. Regularity	81.1%	86.6%	91.1%	84.4%	92.3%	85.5%	92.3%
Prob. Lost of Production	18.9%	13.4%	8.9%	15.6%	7.7%	14.5%	7.7%

hazards are taken, in order to identify arrangements and measures for emergency response and accident prevention in case of an incident/ failure appears.

All in all, to avoid O&M risks and allowing “safety comes first”, requires upon fundamental principles and methods and tools, of risk management for the decision-making on maintenance procedures to be apply.

2. Background

2.1. Condition based monitoring (CBM)

CBM is a predictive and preventive maintenance strategy based upon the technical condition state of the assets, instead of a determined time periodic interval chosen by the last time that the preventive maintenance action was taken or by the age of asset. The technical condition state is determined by the specific parameterized monitoring that reveals the actual on-going health of the asset, such as temperature, corrosion or flow (Rahmati et al., 2018).

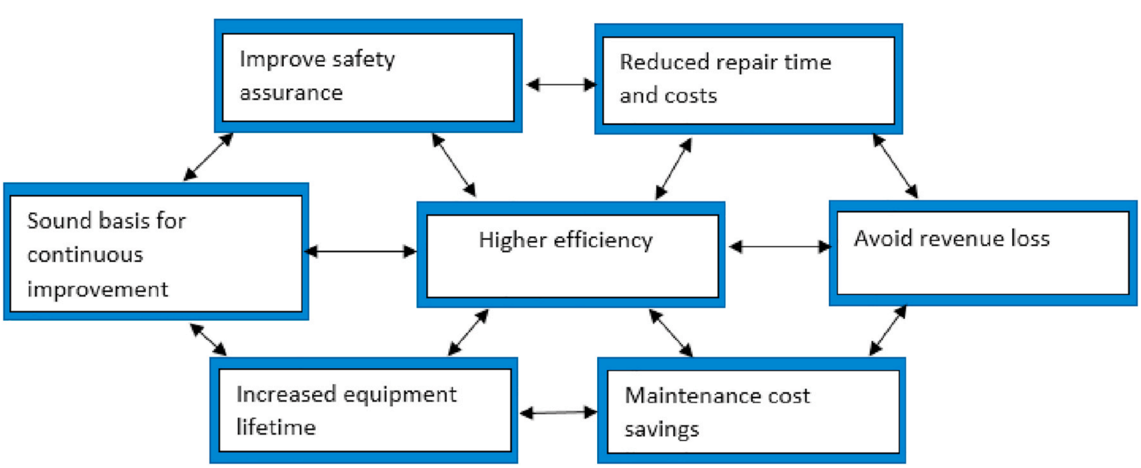

Fig. 2. Core fundamentals and benefits by CBM.

In addition, CBM philosophy assesses proactively the asset health in order to optimize planning and scheduling of maintenance (Hahn et al., 2017). And strives to target early faults ("infant mortality failures") before they turn into critical to allow more precise planning of preventive actions (Amari et al., 2006).

CBM strategy purpose, rest on performing maintenance exclusively when there is aim evidence need it, while ensuring equipment reliability, safety, and reduction of total ownership cost (Shin and Jun 2015).

Meanwhile, CBM shall meet and follow the next fundamentals and benefits (Anders Thorstensen, 2007), see Fig. 2:

Although, CBM failure is thought as a process control assessment, rather being thought of as an event. When functional asset is put into operational service, and at certain point in its lifetime, it begins to fail until it reaches the condition status of functional failure. The key came from building a successful CBM program, from the ground. Which has been summarized into six major steps, establishing an effective, sustainable CBM program.

1. Select the Assets
2. Identify and Targeted Known and Probable Failer Modes.
3. Select CBM Technologies.
4. Set up baseline measurements for Selected CBM Technologies.
5. Establish and Carry out the CBM Program.
6. Act.

2.2. CBM strategy

Oil and Gas production facilities and process production plants are risky and complex systems, consisting of costly and critical production equipment. Even the plants condition state and performance behavior degrades are re-adjusted over time due to the mechanical wear-out, fouling and changes in operation conditions.

The CBM strategy comprises of maintenance tasks being accomplished in response to the deterioration condition state by the performance of an asset/component/element as reported by a condition monitoring process (Norway Regulations to Act, 1997).

Methodology for selection of a suitable CMB strategy, does not vary greatly either it is performed at the design phase, or at a later point with a retrofitting of the monitoring equipment. Although, aim differences rest on the costs, whereas if the decision-made is took at the design phase, it shall be less costly and the CBA outcome could be different.

However, the first step during the process (choosing a CBM-strategy) is to set up whether CBM truly is the best option or not. Then, should follows a multi-step process for choosing of a suitable CBM strategy for a single asset:

1. Identify all failure modes that should be issue for a maintenance development strategy. For instance, applying a Fault Maintenance Element Analysis methodology will be possible to be done it.
2. Find out the P–F interval necessary for each failure modes that permits enough intervention time.
3. Find all the monitoring techniques (i.e. condition monitoring, human inspections … etc) for each failure mode that fulfill with the P–F interval.
4. Performance of CBA, based upon the outcome resulting monitoring techniques. If there are none, a corrective or preventive maintenance must be considered.

Followed by the flowchart (Fig. 3) of the selection process, as below:

Maintenance Strategy as it does, drives CBM, as it was showed above (Fig. 3). From Reliability Center Maintenance Strategy, Condition Assessment, Residual Economic Life Estimation, and Economic Decision to the Computerized Maintenance Management System.

3. Industrial challenge

3.1. Criticality analysis on O&M requirements

3.1.1. Operational philosophy goals

The basic operational and maintenance philosophy for the Johan Sverdrup will be to provide a safe and efficient operation, assuring maximized value from the installed assets over their entered life cycle (50 years), against agreed performance targets and goals.

The requirements to be meet on safe, reliable and efficient operation, the design and layout of all systems, facilities and equipment shall support the operating model and strategy. Which one, is based upon "Health Safety Environment requirements" that follow up an overall HSE zero harm philosophy.

Design of the Johan Sverdrup shall include a fully equipped Living Quarter sized to accommodate and support:

- Campaign Maintenance crew.
- Permanent Operating Manning.
- Peak Manning during turn-around.
- Manning during initial Installation, Commissioning and Start-Up.
- Crew associated with modifications/future tie-ins on further phases.

As well as, the design of the platform shall include a fully equipped control room for permanent operation. In addition, possibilities for remote operation of equipment, facilities and systems related to tie-ins of other near fields shall be provided.

Cost effective solutions outlined in the IO Corporate Initiative and Johan Sverdrup Integrated Operations (IO) Strategy, such as enhanced condition and performance monitoring and closed-circuit television systems shall be utilized as part of the operation philosophy.

3.2. Maintenance strategy

The entirely Johan Sverdrup infrastructure shall be maintained in such a way that safety for personnel, the environment, the equipment and the production is ensured throughout the lifetime of the installation.

Identification of spare part strategy and predictive/preventive maintenance strategy shall be based on operational strategy, criticality analysis, condition/performance monitoring, field experience and seller recommendations.

Although, planned shutdowns shall be minimized by selecting components and materials that eliminate the need for frequent testing, inspection, replacement of expendable parts, etc.

In addition, the planned maintenance programs shall be based on equipment condition and performance monitoring, close seller assistance and equipment, system and discipline co-ordination. Focus shall be put on maintainability during the equipment selection processes, facility design and location/layout work.

3.3. Standardization

Standardization of Equipment, Operating, Control and Surveillance systems shall be required in order to ease the maintenance processes and secure compatibility within the data systems.

3.4. Operability and maintainability of equipment

Operability and Maintainability (O&M) shall prioritized and be a decisive element during design, layout and equipment selection processes, in addition to equipment specifications supporting IO ambitions and condition monitoring requirements.

3.5. Integrated operations (IO)

IO principles and communication technology is a key and

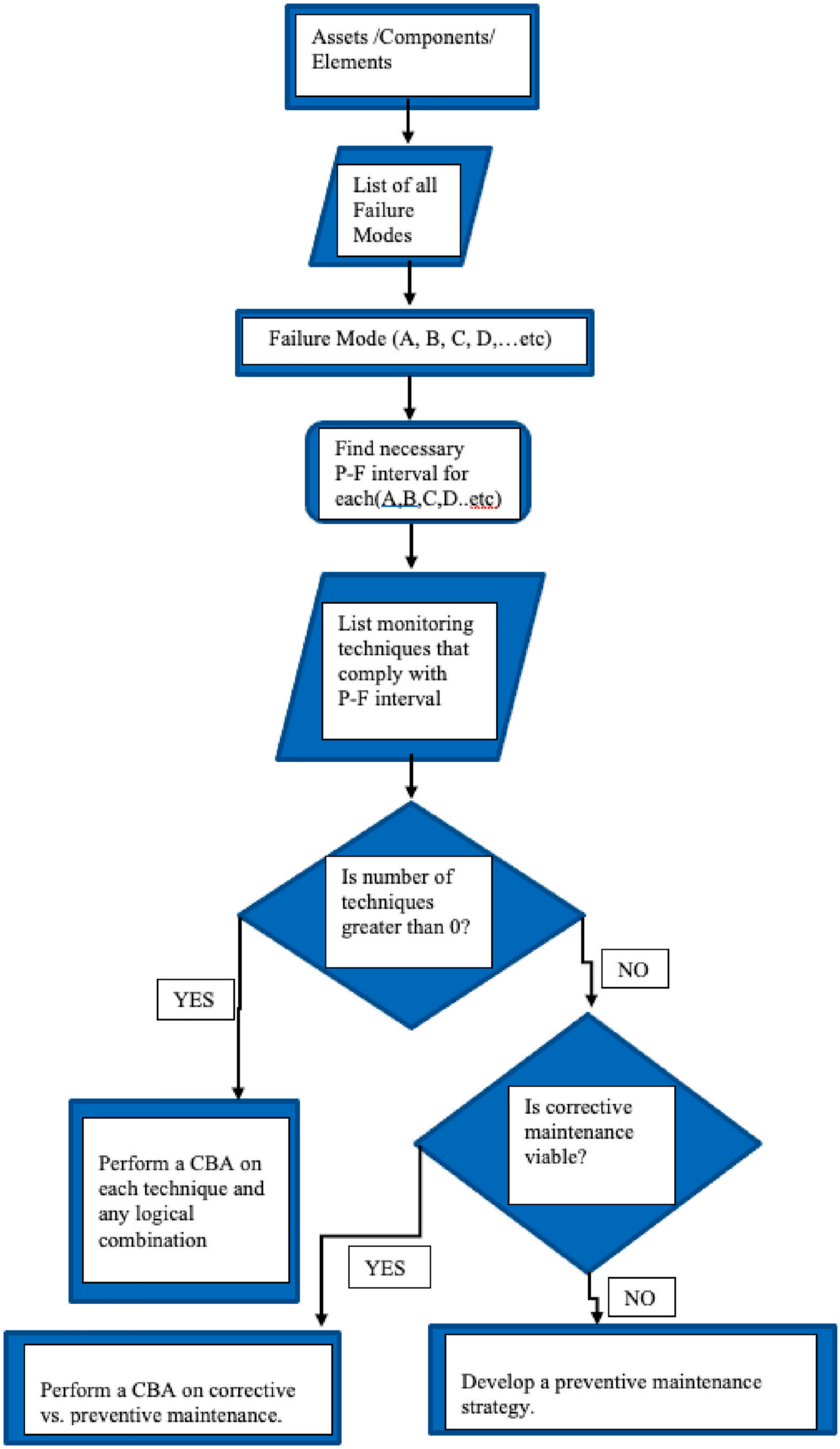

Fig. 3. Selection of CBM strategy simplify (Budgen, 1992).

fundamental tool in the group's operating model and should implemented in all disciplines. IO shall be utilized in the operation of the Johan Sverdrup facilities, and should ensure cooperation, and easy access to internal and external develops solutions. Delivering an optimal integration of technology, organization, work processes and the human factor. In addition, IO will enable the general goal of the integrated ambition stated in the IO Corporate initiative and realization of the potential value creation inherent in collaboration, during execution of work processes and activities.

Key tools are information and communications technology. There are plans for a variety of systems for monitoring and control of plant condition and performance, transfer of real time data from the plant, facilitating of information for the company's work processes, remote access and remote control, high degree of automation, intra- and inter-organizational cooperation, and an effective development and use of human resources (O at the Johan Sverdrup, 2014).

The operation of the Johan Sverdrup facility, shall be optimized and contributed with respect work process, collaboration tools and data management through:

- To lay the foundation for High-Quality interaction sea-land and to create a common situational awareness between operators, suppliers, resource centers and other actors involved.
- Capability to enable online remote condition and performance monitoring of selected equipment, systems and processes in the multi-asset onshore centers of each operator.
- Risk awareness and proactivity through handling real-time data and historical data.
- More robust of the operative paragraphs of information, knowledge and central expert support for needs.
- Facilitate the tasks can be performed where it is most effective, and that more tasks can carry out on land. These factors will contribute to improving security and reservoir recovery, higher carrying capacity and reduced investment and operating costs (O at the Johan Sverdrup, 2014).

4. Methodology

This section describes and settles the approaches made. Starts with explaining the methodology and definition of safety objectives (risk matrix), follow by description model of the Design for Reliability and Reliability processes, followed by a Maintenance Management model, the applicability of the LCC analysis and the need to designing maintenance alternatives.

1) Risk Acceptance Criteria (Risk Matrix): The methodology for determination of criticality of failure, can be summarized into a Risk Matrix, which one uses of risk-based method. As well as, Risk Matrix is very useful for any kind of maintenance. And for the description of the operations carried out and the good practice used in design and specification technical requirements.

We should use a risk matrix to identify and present all critical parts at the Johan Sverdrup Oil&Gas field. Where the risk matrix acts as function between the occurrence of failures modes (Probability of Failures) and severity of consequences (Consequences of Failures), see Fig. 4.

This matrix shows standard and basic risk acceptance criteria, that can easily be used for any single component/element for the Johan Sverdrup Oil&Gas field. As we can observe into the figure(Fig. 4), when the severity of consequence is high and the likelihood is possible, the risk is considered unacceptable. So then, the risk decrease measures should be carried out to reduce the risk to the acceptable level. Although, with the severity of consequence being low and the likelihood being possible, the risk is deliberated acceptable. However, reasonable measures should be taken as well, to reduce the risk as low as possible (ASLSP).

Therefore, if the overall maintenance of the Johan Sverdrup Oil&Gas field becomes over time with a total risk ASLSP, the total on-going and expected future costs, will be decreased considerable.

***2) Maintenance Management model*:** Achievable goals mentioned (on Section 3), we are to set up a structured maintenance management program. But initially we have to identify strategy we want to put into the essence of our maintenance program. In 1997 Norwegian Petroleum Directorate developed maintenance management model (Norway Regulations to Act, 1997), so we will refer the research work to it. We have to ensure the necessary resources such as organizational, materials and supporting documentation. In compliance with the strategy we carefully plan out our activities and execute the tasks planned. In order to improve work maintenance activities, is key to generate reports, conduct thorough analysis, and implement necessary improvement measures.

The goodwill to carried out straightly the maintenance management model shown, allows to conduct risk analysis level at the of chain, and so, reveal all the related risks.

Consequently, the objectives of this model are to increase availability, reduce risk and improve reliability of systems as a result (Zhamangarin et al. Andrea).

3) ***LCC perspective and Designing Maintenance Alternatives*:**

Life Cycle Cost (LCC) Analysis is affordability analysis tool, that considers assets costs and long term financial planning, where key information given, comes from the cost profile curve describe over the Life Cycle itself. LCC also called "Cost Benefit Analysis (CBA)", acts as decision-making tool when diverse alternatives are under study consideration and select the best investment of the alternative chosen.

LCC refers to the overall associated costs of a product/system over a defined life cycle (e.g. all acquisition costs related, OPEX …) and the utilization of a product/system over an assigned period of the product/system lifetime (Murthy et al., 2002). LCC can be perceived as tool that includes both, "forecasting" and "costs tracking" on a whole-life basis (ANNI and PETRI, 2014). As well as, used to account and quantify the total costs of a product/system throughout its whole life cycle, so knowing the LCC of the product/system as basic one requirement when one is take into account for example, offering one's capacity for use by the other organizations in the supply chain.

The essential thing at the LCC is to realize the interaction by the "cost drivers" that cumulate among the relevant stakeholders during the different life cycle phases.

The Operating Expenditure Costs (OPEX) drivers can be divided in the following grouping:

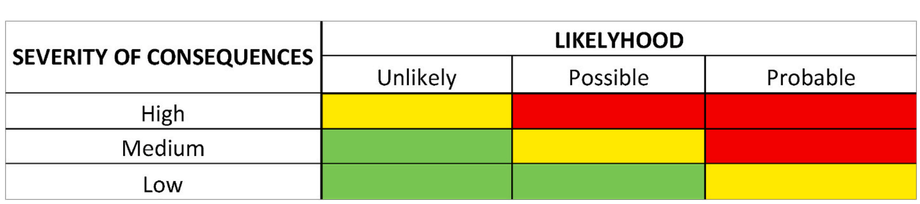

Fig. 4. Risk matrix.

- **Man-hour costs:**
  - Corrective maintenance man-hours crew.
  - Preventive maintenance man-hours crew.
  - Man-hour rate operator.
  - Personnel transport.
- **Spare parts and consumables consumptions costs.**
- **Logistic support costs** (e.g. ROV, supply boat, support vessel, helicopter costs).
- **Energy consumption cost.**
- **Insure Costs.**
- **Onshore support costs.**
- **Cost of deferred production.**

After mapping all operational costs drivers (listed above), furthermore in order to estimate further costs, the key feature from the LCC is the monitoring costs during a product's/system's life cycle. Hence, it's crucial to know the cost caused for a particular product/service and to comprehend the behavior of the different cost elements along the different stages of the Life Cycle.

The endeavor is to monitor the actual costs versus the predicted LCC, and to calculate cumulative costs all over a product's Life Cycle (see along Section V).

As such, shall be denoted that the monitoring costs are not consistent concerning to different costs factors since costs related to O&M use to be monitored precisely, rather other cost factors (i.e. indirect costs).

Date collecting can indicate the link between the way of using or maintaining products life and the carrier cost drivers. LCC data are using in the Oil&Gas Industry to choose factors affecting product reliability and as essential data for future provisions. Besides that, possibilities to use empirical data by supplier's rely on the incoming information obtained by customers during a product/system LC and often the stipulation of information is deficient perceived. This lack of communication between suppliers and customers, likely will decrease in the future, due to the full implementation of monitoring of LCC.

Information data prediction in advance with LCC, are key during decision making, purchasing a product, and scheduling maintenance steps or even optimizing design. In order to make better decisions based by the partners available information, knowledge and intelligence is vital.

The decision making itself is often solely based on a compound of "tacit knowledge" gained and achieved over the years and/or recommendations from the original equipment manufacturer (OEM)/supplier. Being capable to make critical decisions more robust, faster and more reliable. They are also able to make critical decisions more robust, faster and more reliable. In summary, a production assurance strategy in a total LCC perspective is the key to create **business value** by production assurance.

As was explained and stated previously, in order to carry out LCC Analysis is need it to defined the input (i.e. number preventive rounds/year, total failure rates …) data of the LCC analysis model to be developed. Fig. 5 the input data graph for both Alternatives (1&2) of the LCC Analysis model:

As we can see from Fig. 5, the number of preventive rounds/year has been progressively

increased, in order to contra rest the degradation and deterioration speed curve along the lifetime of the Oil&Gas Platforms, where the knowledge-base adopted of the input date values assigned (Nilsson and Bertling, 2007).

As older the installations get, much increase the failure risks. In parallel to that, total failure rates have been assumed and extrapolated according to the bath curve (failures/year) distribution;

$$\lambda^{2016-2024} = 1,\ \lambda^{2025-2036} = 0.75,\ \lambda^{2037-2048} = 0.5$$

$$\lambda^{2049-2056} = 0.75,\ \lambda^{2057-2063} = 1,\ \lambda^{2064-2068} = 0.5$$

Major Repairs (=P25x $\lambda^{n=year}$) and Minor Repairs(=P75x $\lambda^{n=year}$) being failures/year, that being follow respective probability distributions(25% vs. 75%) multiple by the bath curve($\lambda^{n=year}$) failures/year values.

Lastly, for each case study (Alternative 1 vs.2), has been set up as inputs, hypothetical prices of Oil&Gas into the global market. As well as, has been assumed that Alternative 1, suffers technical disturbance ("outside scope of O&M contract" i.e.: delays-time maintenance, impacting major investments and costs on spare parts) in compare with Alternative 2, meaning that Alternative 1 will have 120% major costs ratio($/year) over their Major Repairs.

5. Analysis

Development of an Oil&Gas field is a process which stretches over a long period of time. Requires a study analysis and research work on development the life cycle field economies are estimated with a model approach forecasting the future Integrity Maintenance Reliability (IMR) costs for different intervention strategies. A good maintenance model, shall be take it into account challenges for the design of appropriate Maintenance Management System (MMS) that would be recognized and accepted by the petroleum industry in Norway. The analysis made has balanced conservative measures due to HSE policies ("Zero Harm Philosophy") and relative progressive actions on boosted production.

The estimation of the entered analysis cost, was based on basic

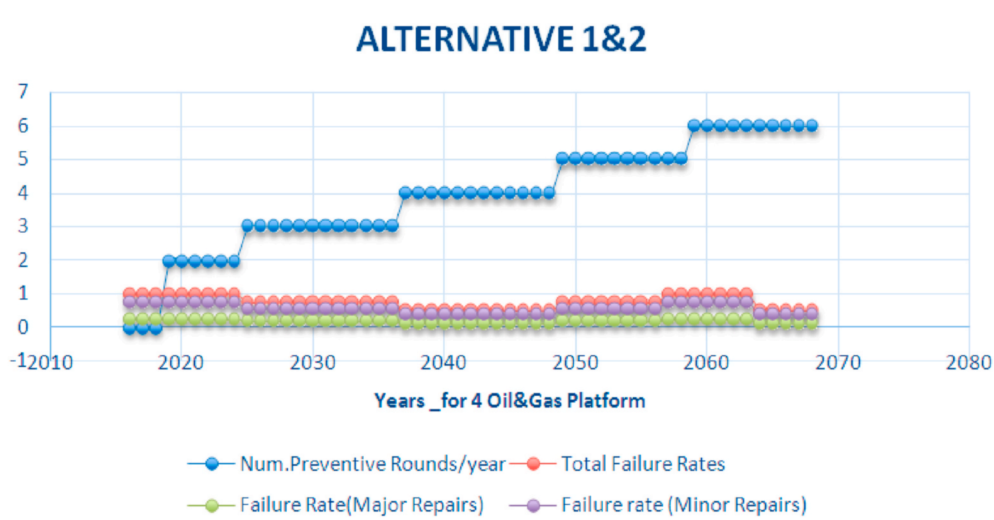

Fig. 5. Input data values for the LCC Analysis model (Murthy et al., 2002).

fundamentals:

- LCC Analysis.
- Downtime Analysis Cost.
- CBA (Cost-Benefit-Analysis).

5.1. LCC analysis

The Life Cycle Cost(LCC) and profit that carried out the whole Johan Sverdrop, has been estimated under four case studies, with essential combination on Oil and Gas prices, that might be occur. Therefore, the model made has been used to take into account the value of money in time. Being the LCC model the sum of the discounted capital and operational expenditures, over the lifetime of a system or product. In the context of the LCC Maintenance Cost, has been included fully into the OPEX. Coming up with a global LCC as:

(1) LCC(Billion of $) = CAPEX + OPEX + REVLOSS

The model made, includes Operating Costs Corrective (Minor and Major) and Preventive Maintenance (Transportation + Man-hour) Costs, four cases of hypothetical prices(Oil&Gas), as well as Deferred production costs and the overall costs before/after discounting.

The assumptions carried out to develop the model, are from Number of preventive Maintenance rounds/year from 2 to 6, total failure rate (1, 0.75, 0.5), downtime major repairs (15days/failure), and downtime minor repairs (2 days/failure) and the Mean overall downtime (5,25 days/failure).

Therefore, the total operating expenditure costs (OPEX = Corrective & Preventive Maintenance) for each Alternative (1 vs. 2) can be summarized on Fig. 6.

As we can observe from Fig. 6, Oil&Gas Offshore Platforms requires more preventive maintenance costs, due to are installations riskier than OWT's. Hence, investing in preventive maintenance, adds more safety.

It shall be denoted, that OPEX calculations have not included (Spare parts and consumables consumption cost + Insurance costs + Onshore Support Cost), although, it has included Energy Consumption Cost.

Fig. 7 the entered percentage distribution of OPEX (Total Operating Cost Corrective Maintenance + Preventive Maintenance + Energy Consumption Costs) for each Alternative(1 vs.2):

As we can observed from Fig. 7 above, stability on costs, happens after year (2024) and forward. Since, has been passed the crucial years ("Early Life = Infant Mortality Failures") in production. Also, years from 2016 to 2019 reflects a negative difference, being Alternative 1 a bit higher than Alternative 2.

The global LCC model, has computed four case study, at different Oil Price (40, 50, 60, 80$/bbl), and Gas(0.35, 0.40, 0.45, 0.50$/Sm3), as well as has been included the percentage of prob. of lose per year and their own discount rate.

As we see above (Figs. 8–10), the early phase (2019–2022) carries potential costs, which ones drop down from 2023 to further years. Case 1, looks to be the cheapest cost accumulative but may be less competitive for selling out large volumes of Oil&Gas to the Market.

5.2. Downtime analysis cost

Downtimes are huge cost driver to any production installation facility, as can be this one. Along this case study, downtimes costs identify, are limited to the reduction of production, so, meaning a loss of revenue. It shall be denoted that loss of production will be recovered either regularly each year, or by the end of the plateau period life. Due to variance of the net present value(NPV) along the time, the monetary income loss is real, even for having a total volume of produced hydrocarbons is the same. What matters it's the NPV real though the production asset.

The estimated expected revenue losses (REVLOSS) for the produced hydrocarbons (Oil + Gas), has been calculated from the following formula where F(i) probability of production loss in year(i), V(i) is volumes (Oil + Gas), PR(i) is the oil and gas price respectively, r is the discount rate and a(j) is the volumes (Oil + Gas) recovered in the following years. See next equation:

$$REVLOSS = \sum_{i=1}^{n} \frac{F(i)V(i)PR(i)}{(1+r)^i} - \sum_{i=1}^{n} F(i)^* \sum_{j=i+1}^{n} \frac{a(j)PR(j)}{(1+r)^j} \quad (2)$$

Hence, given outcome of clean on the Real Oil&Gas volume to be recover each year.

The result of the overall REVLOSS on each case, can be found on next graph (Fig. 11):

The outcome obtained into Fig. 11, shows losses from unexpected "Downtime" are enormous, especially during early years ("early life failures = infant mortality") of production. What means, a call to implement strong "CBM Strategies" and O&M Philosophies, which ones shall save potential cost for further phase. Hence, from early to medium phase (2019–2031), demands appropriate maintenance programs.

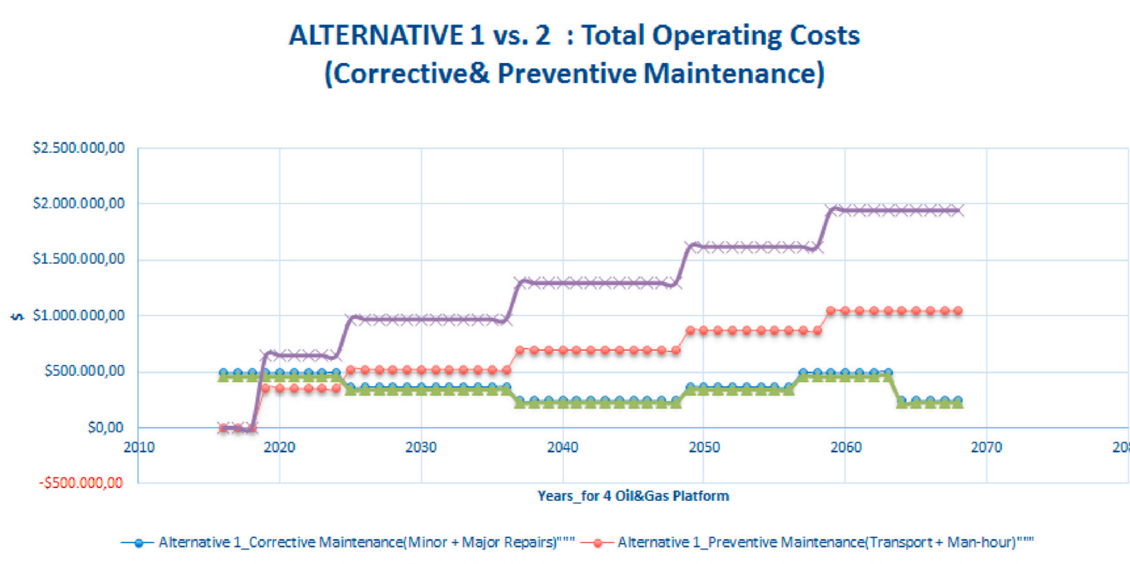

Fig. 6. Total CAPEX (Corrective & Maintenance) for both Alternatives(1 vs.2).

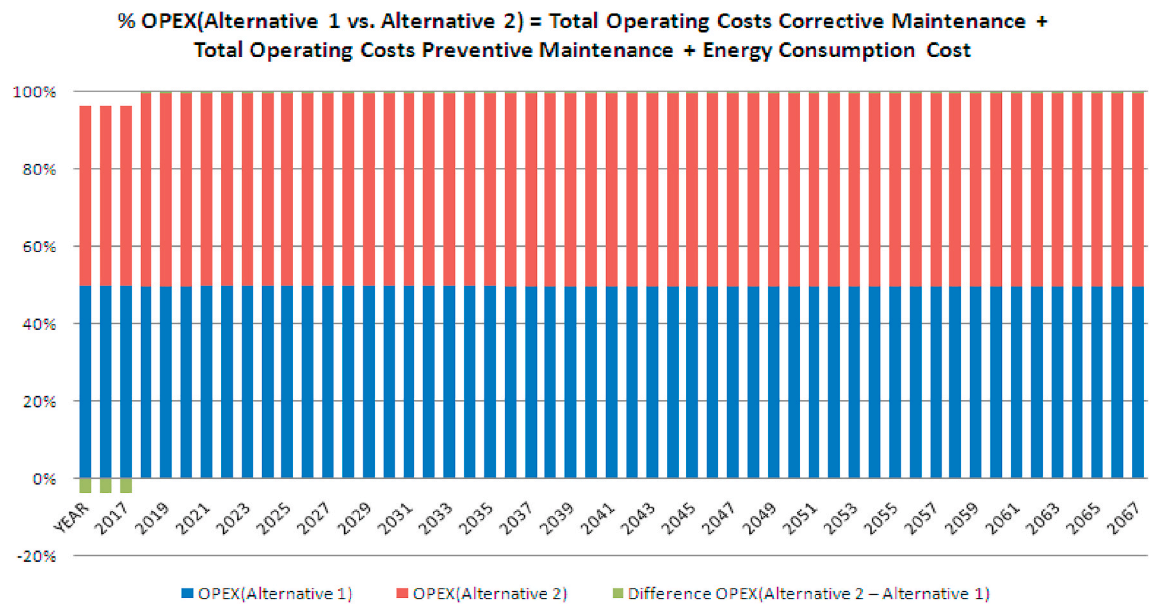

Fig. 7. Total % OPEX(Alternative 1 vs. 2) including Energy Consumption Costs.

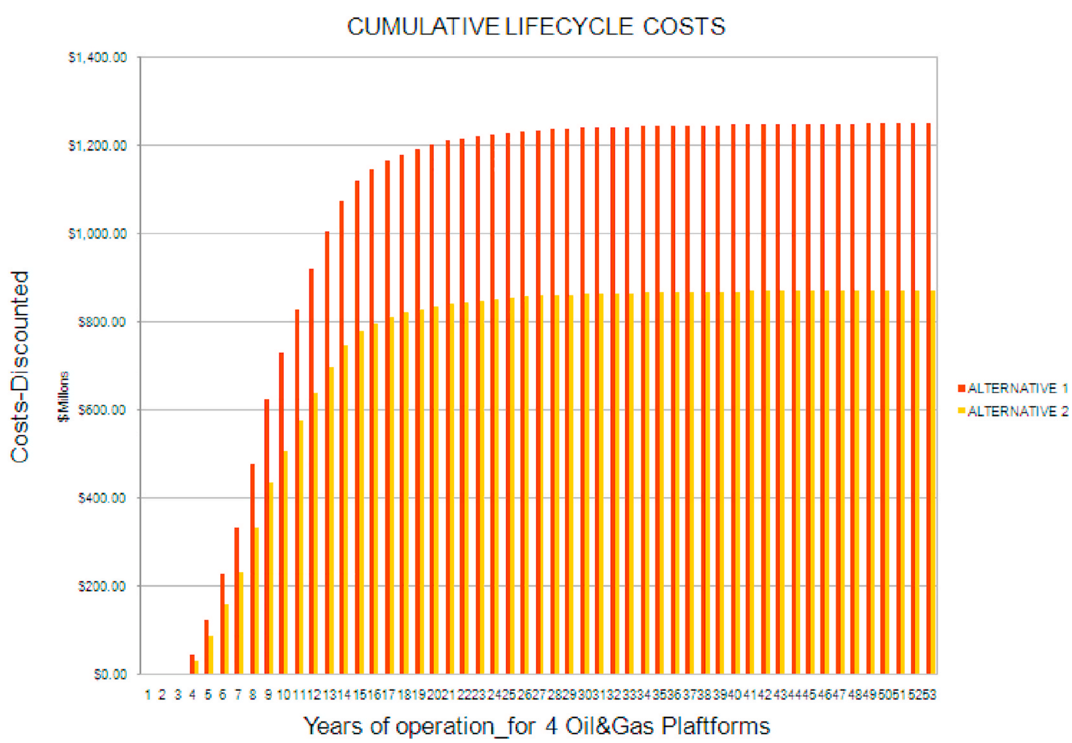

Fig. 8. Cumulative Lifecycle Costs (Cost Discounted vs. Year of Operation).

In addition, in terms of clean **Benefits** (Total Numb. Of Barrels & volumes Produce – Total Cost to Produce – REVLOSS), the calculations obtained, tells that **CASE 3** (Gas:0,45$/Sm^3 and Oil: 0,60$/bbl) can be most optimal achievable value for the whole benefit accumulated (**2,40173E+12 mill $**).

Quick conclusions that we can draw easily, are that, for lower Oil-&Gas Price the losses from unexpected downtime are much lower, rather than Oil&Gas Price higher, where the Benefits are great (CASE 3). The balance, between optimality shall rest between CASE 3 to CASE 4 (Gas: 0,50$/Sm^3 + Oil: 0,80$/bbl).

- **Deferred Production Costs**

As was explained before, downtimes have direct impact on the production revenue income. Thus, deferred production costs must be quantified, in order to measure the losses. Along the analysis model, has been assumed two different scenarios for each respective Alternative, see on next table (Table 3) below:

The overall result of the Deferred Production Costs for both alternatives (1 vs. 2), is represented on next graph below, Fig. 12:

As we can identify from the graph (Fig. 12) above, the Alternative 1 becomes the disadvantage one, in compare with the Alternative 2. As well shows the Alternative 1, as much downtimes days, as costly is the deferred production cost.

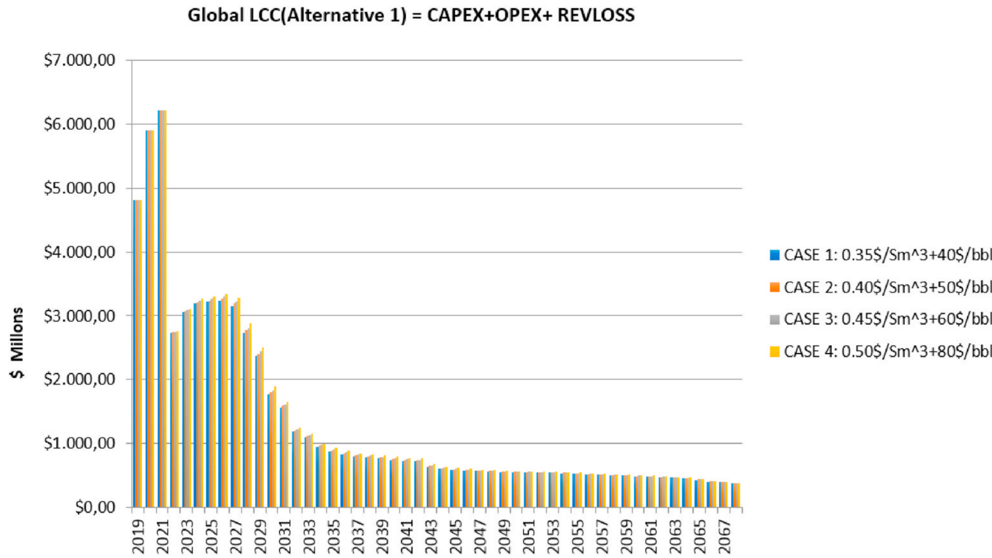

Fig. 9. Global LCC (Alternative 1) during 50 Years of production.

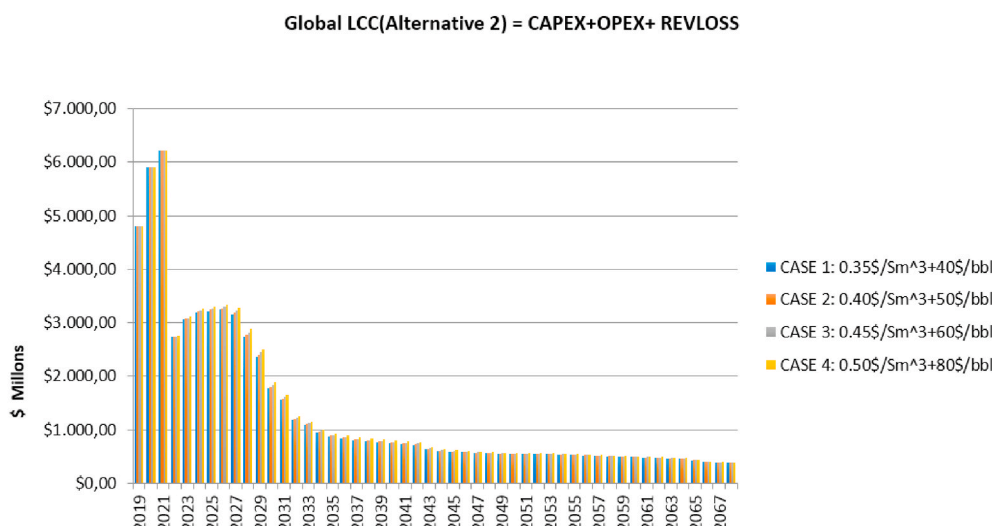

Fig. 10. Global LCC(Alternative 2) during 50 Years of production.

5.3. CBA (Cost-Benefit-Analysis)

The CBA is carried out to determine whether a planned action is profitable or not (Andersen and Rasmussen, 1999). CBA approach, to estimate the strengths and weaknesses of alternatives (1 vs.2) used to determine options which deliver the best approach to achieving benefits while preserving savings. The aim of CBA is to help minimize risks and maximize gains both for the project and the organization itself.

There are two main drives in using CBA:

- To determine if an investment/decision is sound, reasonable and feasible by figuring out if its benefits outweigh its costs.
- To offer a baseline for matching investment/decision by determining which total expected benefits are greater than its total expected costs.

In summary, CBA is an analysis of the expected balance of benefits and costs, including an account of any alternatives (1 vs. 2) and the status quo. Helping to forecast whether the benefits of a policy outweigh its costs, relative to other alternatives.

All in all, CBA can be considered as useful indicator tool to measure a project development beforehand, in order to assess a “go or not go” investment decision.

As basic requirement, to perform a CBA it is essential to have as precise estimates of the costs as possible.

For the present research work made, has been computed two type of scenarios (1 and 2), based on two LLC Alternatives that haven calculated. Here below, the table summary of the results obtained:

Also, is represented on the next figure:

From the items (Table 4 and Fig. 13) above, clearly summarizes overall core results from two types of Alternatives (1 vs. 2), that have been demonstrated.

6. Discussion

6.1. LCC analysis

LCC Analysis has visualized consequences for two different design alternatives, which one has proved the strengths and weakness that each alternative carries. Each LCC Analysis models, settles operating costs on corrective and preventive maintenance bases.

The cost of maintenance is high, approximately around 30–40%, so

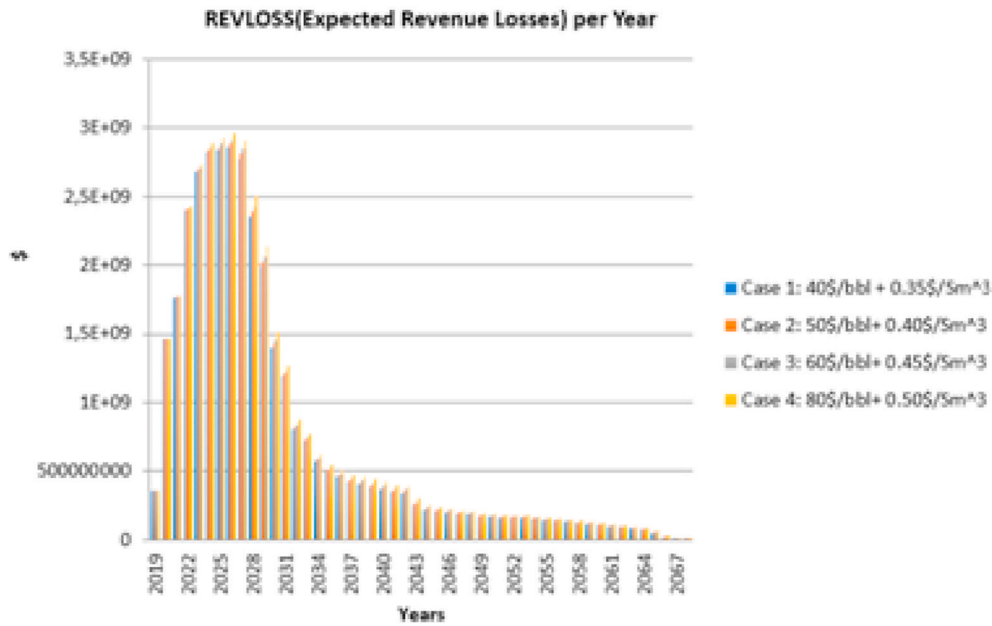

Fig. 11. REVLOSS estimate per Year.

Table 3
Downtime input date (Alternative 1 vs. Alternative 2).

	ALTERNATIVE 1	ALTERNATIVE 2
Downtime Major Repairs(day/failure)	15 days	10 days
Downtime Minor Repairs(day/failure)	2 days	1.5 days
Mean Overall Downtime(days/failure)	5.25 days	3.625 days

while designing and selecting appropriate equipment and production technology systems, one has to perform LCC Analysis to arrive at the most optimal solution (ALTERNATIVE 2), with a Benefit-Cost Ration of 4.03, in compare with 2.81 from ALTERNATIVE 1.

6.2. *Downtime costs*

The downtime analysis cost, has calculated the essential parameter that Downtime issue (Shut down, Equipment failure, Preventive/

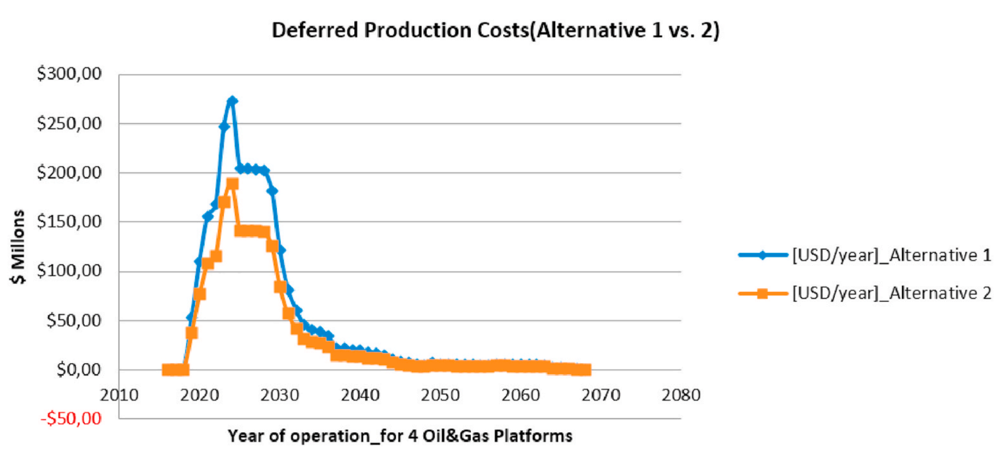

Fig. 12. Deferred Production Costs (Alternative 1 vs. 2).

Table 4
CBA on the Total LCC for two alternatives (1 and 2).

# Cost-Benefit Analysis (CBA) on the Total LCC for O&M:				
ALTERNATIVE	LIFE CYCLE COST ($)	BENEFIT/REVENUE($)	NET BENEFIT($)	BCR
1	$54,271,012,042.26	$152,365,044,073.00	$98,094,032,030.74	2.81
2	$37,766,451,365.54	$152,365,044,073.00	$114,598,592,707.46	4.03

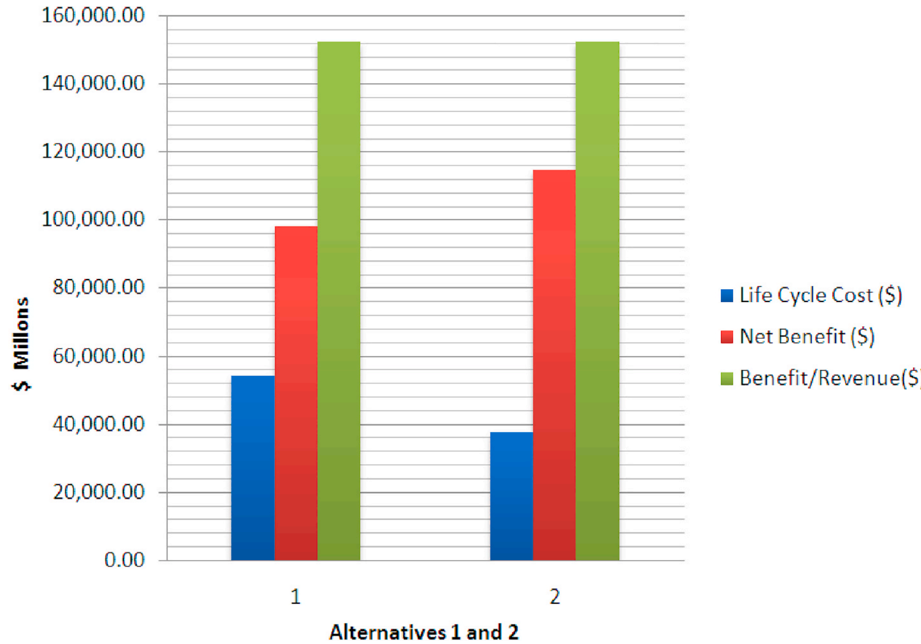

Fig. 13. CBA on the Total LCC for two Alternatives (1 and 2).

Corrective Maintenance …), can cause at different Oil Prices (40$/bbl, 50$/bbl, …) a potential economical lost. Which one, creates a potential "Lost Revenue" along the chain of business value and raising the LCC.

So, as we observed a downtime is immensely expensive in the order of 100.000 [$/hr] on average. In addition, a maintenance task should not be "postponed", due to there is an increased risk of having "functional failure". This could result in both added cost of corrective maintenance and downtime, in addition to possible safety issues (Andersen and Rasmussen, 1999).

Additionally, happening a downtime **CASE 3 (Gas:0,45$/Sm^3 + Oil:0,60$/bbl)** is the most beneficial, on the rest of the CASES (1,2,4) the losses are much higher.

In addition to that, has been proved along the deferred production cost analysis, that as much days of downtimes, as higher (Alternative 1) becomes the deferred production costs.

7. Conclusion

The main objectives and goals concluded are summarized on the next bullet points:

7.1. CBM strategies and benefits

As has been demonstrated on previous sections above, CBM methodologies, procedures and software means (i.e. SCADA) can contribute straightforward to reduce costs and potential risks. CMB can measure at real-time bases (failures, alarms … etc), therefore, it will be more efficiency, intelligent, and cheaper to adjust the input data values (Nº Preventive rounds/year, Nº Major Repairs, Nº Minor Repairs, Total Failure Rates …) in advance, over the Maintenance Management Planning. All in all, having at real-time (failures, alarms …) it's a continues real feedback on input date values.

In addition to that, the concern beyond on implementing appropriate CBM Strategy philosophy, is not to prevent the failure process that starts in the first place, but to take action before the failure reduces the condition state functionality of the asset below the desired condition state level (Apeland and Aven, 2000). So, the maintenance job is not to "fix it when already it fails", if not to avoid failure altogether. Therefore, "predictive maintenance" is the core value of CBM as whole.

Hence, CBM has the ability to decrease both times to repair and the time between maintenance activities, as resultant of savings in labor, logistics costs and reduction of downtime production losses (Jardine et al., 2006). As well as, strong measures on CBM strategies and maintenance programs shall be applied on early to medium phases, as result bringing the cost down and performing safety in the long term. CBM system as whole, brings the possibility to increase the reliability management system control.

7.2. Integrated operations (IO)

As was observer from the analysis section, Alternative 1, was costly, in compare to Alternative 2, meaning the necessity to reduce the 120% major costs ratio($/year) create on Alternative 1. To do that, is need it, that any operator shall guaranty their IO's, should not seek to revise their whole organization, but rather do it one step at the time. To do it, it shall base upon the O&M best practice guidelines, where are reported and stated all the integration from Operations, Maintenance, Engineering, Training and Administrative roles. Although, weaknesses will come from O&M integration from repairs and substitution of spare parts, due to it's difficult because these activities usually are done on a "time-and-materials basis". Thus, lacking of robust IO techniques and appropriate provision of the operational activities can result in an increase of major costs ratio, as was happened on Alternative 1.

By another side, Offshore production operations in harsh environments (i.e. arctic offshore locations) call for a much stronger focus on technical condition state, technical integrity and maintenance efficiency of their assets on those remote offshore locations. By implementing stronger IOs, the maintenance management strategy may be robust and flexible.

Therefore, all in all, "IOs philosophy" is based on promoting work best practices for utilizing competences and mobilizing specialized knowledgebase irrespective if disciplines, specific locations-environments and company borders (Cibulkaet. al, 2012). Turnover, into lower cost (reducing major costs ratio) originated.

7.3. Reliability and redundancy

In terms of "Reliability" and "Redundancy" the entered Oil&Gas Industry requires a change, not only to justify the reliable design … but to focus more on human-centered designs. As was indicated on Fig. 6

(Production assurance in a total LCC perspective), the lost revenue can be given by Equipment Failure for instance.

Equipment and Systems must be designed for reliability with a specific target value – for instance, 99% reliability for 30 days, in order to avoid Equipment/System failures situations. Further, such measures outcomes of reliability should be incorporated into the design process early on, rather than having equipment be designed first ("with unknown reliability") and then tested for reliability ("to know it") once completed. "You first prove the reliability target, then you create a design that fulfils that reliability target". As well as, the idea of setting an appropriate reliability target is first at all to make it fail the Equipment, to identify the weakness of the Design, and therefore, learn from it.

Therefore, CBM shall be based on appropriate Design for Reliability (DfR) beforehand, where the Reliability specifications set are Quantitative in Nature. Concluding that essential elements of Reliability specifications (Probability of Survival, Time in Service, Operating Conditions, and Confidence Level) are the key to a successfully of an Operational Maintenance Philosophy.

7.4. Operation and maintenance programs

As it was demonstrated, the maintenance models are stochastic life cycle cost (LCC) models dependent on Reliability and Maintenance processes. The results indicate that Condition Monitoring (CM) of the components and/or elements results in an economic benefit, due to implementation of right measure (CBM Strategies + O&M programs) over the lifetime (50 Years) and that it reduces the risk of high long term maintenance costs.

By another side, the Cost-Benefit of inspection based on condition based maintenance techniques and continues monitoring of the overall "Assets" is much dependent on the Reliability assumptions, as well as the initial design assumptions over the concept selection.

The results obtained indicate under which conditions the Maintenance strategies are optimal, and how these strategies can reduce the Economic Risk, known as Risk Expenditures.

Finally, the overall conclusion that we could extract on CBM programs and their implementation for a project of Johan Sverdrup is to implement Reliability, Availability and Maintainability. Analysis, to achieved the best O&M model during their Lifetime. Where the settled up basis and philosophies of the CBM strategy mechanism built, are crucial. Being a good maintenance strategy, as is defined as: "a low-cost absence of events".

8. Future performace outlook

Operators must put on value the specific expertise's on Suppliers ("Sub-Contractors") as well as their Technology, in order to carry out safety operations and guaranty a reliable cost, adjusted to the mature development of the Oil or Gas field.

Finding out profitable mature asset starts with lifting efficiency technology, reservoir monitoring systems and well data traceability visualization software's, which ones can easily measure the safety performances and the production rates for Oil or Gas fields.

Strategies on lowering the CAPEX expenditure will relay of technological mature expertise to aim for quick and profitable win-win investments scenarios.

A switch on the industry, shall come from leading production optimization equipment and software solutions, so helping to reduce operating expenses, minimize production decline rates, and decrease damage risk caused by sand, paraffin, and corrosion. The ones originated a faster degradation on the technology and equipment into Sand Oil&Gas fields for instance. Therefore, adjusting "the nature challenges vs. equipment functional requirements" to cover the demand of the production needs on specify site, is going to be goal set on saving investments and creating specific technology on those Oil&Gas fields. In summary, pursue on conventional equipment-technology is going to be step back, due to the faster deterioration for this not-specify equipment-technology, as result causing higher operating expenses during life cycle production of the specific field.

Concluding that the boosting productivity by building performance that's essential. It shall start from lower investments techniques, quicker ones, such as specific methodically industrial techniques, that give an industrial safety behavior feedback return input, improving performance, reduce costs, and increase cash flow in the long term.

Oil&Gas challenge fields (Sand, Artic …) requires a higher degree of CAPEX investments, as well as development specific equipment-technology and methodologies techniques in site, which ones firstly will re-establish decreasing costs during the production life cycle of the field, and secondly, adjusting to the production hazard environmental needs. In addition to that, those challenges fields will need to develop higher reliability and availability of equipment's parts(components/elements), in order to allow much shorter maintenance intervention periods, as challenge as can be under ice. Also, the integrity of the assets, shall target all the production functionalities on the specific reservoir field (Oil vs. Gas), in upstream (from wellbore to the reservoir) and downstream (logistics to production facilities), and with continues bear in mind about the environmental conditions (ice, higher salinity …) at any phase development of project.

Credit author statement

Jose V.Taboada: Writing – original draft preparation. Vicente Diaz-Casas: Reviewing and Editing, Xi Yu: Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We thank Gonzalo Diz-Lois Palomares (Senior Structural Engineer at Olav Olsen AS) to his contribution and help and Prof. R.M. Chandima Ratnayake (UiS) for his email advise. This paper has been funding for open access charge: Universidade da Coruña/CISUG.

References

Amari, S.V., McLaughlin, L., Pham, H., 2006. Cost-effective condition-based maintenance using Markov decision processes. In: RAMS'06. Annual Reliability and Maintainability Symposium, vol. 2006. IEEE, pp. 464–469.
Anders Thorstensen, Tom, 2007. Lifetime Profit Modelling of Ageing Systems Utilisinginforma- Tion about Technical Condition. Ph.D. thesis. NTNU.
Andersen, T.M., Rasmussen, M., 1999. Decision support in a condition based environment. J. Qual. Mainten. Eng. 5 (2), 89–100.
Anni, L., Petri, S., 2014. Present and Future of Life Cycle Costing: Reflections from Finnish Companies. Tamper University of Technology, Cost Management Center (CMC), pp. 282–292.
Apeland, Sigve, Aven, Terje, March 2000. Risk based maintenance optimization: foundational issues, 67 (3), 285–292.
Aven, Terje, 2015. Risk Analysis. John Wiley & Sons.
Aven, T., Zio, Enrico, 2018. Knowledge in Risk Assessmentand Management. John Wiley & Sons Ltd. Published.
Budgen, P.J., 1992. June). Why risk analysis?. In: IEE Colloquium on Risk Analysis Methods and Tools. IET, 2-1.
Cibulka, et al., 2012. CBM for offshore equipment. Model. Ident. Contr. 33 (2), 69–86. ISSN 1890-1328.
Eikje, E., Nedrelid, T., Bratli, E., Kulkarni, R., Fylling, A.E., Lyse, O., Aarrestad, H.D., 2020. May). Towards a recovery ambition of more than 70% for the johan Sverdrup field. In: Offshore Technology Conference. Offshore Technology Conference.
Florian, Mihai, Dalsgaard Sørensen, John, 2017. Risk-based planning of operation and maintenance for offshore wind farms. 14th Deep Sea Offshore Wind R&D Conference. EERA DeepWind 18–20. January 2017.
Hahn, B., Welte, T., Faulstich, S., Bangalore, P., Boussion, C., Harrison, K., et al., 2017. Recommended practices for wind farm data collection and reliability assessment for O&M optimization. Energy Procedia 137, 358–365.

Jardine, A.K., Lin, D., Banjevic, D., 2006. A review on machinery diagnostics and prognostics implementing condition-based maintenance. Mech. Syst. Signal Process. 20 (7), 1483–1510.
Murthy, D.N.P., Atrens, A., Eccleston, J.A., 2002. Strategic maintenance management. J. Qual. Mainten. Eng. 8 (4), 287–305. https://doi.org/10.1108/13552510210448504.
Nilsson, J., Bertling, L., 2007. Maintenance management of wind power systems using condition monitoring systems—life cycle cost analysis for two case studies. IEEE Trans. Energy Convers. 22 (1), 223–229.
Norway Regulations to Act Relating to Petroleum Activities, 27 June 1997.
PDO at the Johan Sverdrup-feltet PL 265, PL 501, PL 501B og PL 502 PUD del II - Konsekvensutredning November 2014. RE-PM312-00126.
Rahmati, S.H.A., Ahmadi, A., Karimi, B., 2018. Multi-objective evolutionary simulation based optimization mechanism for a novel stochastic reliability centered maintenance problem. Swarm and Evolutionary Computation 40, 255–271.
Shin, J.H., Jun, H.B., 2015. On condition based maintenance policy. Journal of Computational Design and Engineering 2 (2), 119–127.
Rauan Zhamangarin, Denis Komoza, Mari Joo-Mee, and Paola Andrea: reportOperation & Maintenance Management of the Statfjord Production Facility. Report at the Operation and Maintenance Management course(MOM 460).