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MASTER'S THESIS

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Abstract

In offshore production installations, numerous platforms, facilities, systems, and equipment's are approaching or already exceeded their original design life. The industrial product is design for limited timespan and concluded by the phenomenon of decommissioning. When the system approaches that limit, the dominate ageing aggregation affect the performance parameter of the system and resulting in reliability, integrity, safety, and commercial issues. The process of life extension mitigates the effects of ageing mechanism and extend the life or safety limits of the system. The LE process also reduces or diminish the inherit risk possessed by system during their original design life and makes sure the adoption of advance technologies and consideration of new standards and codes.

The current thesis explores the industrial practices for extending the life and safety limits of offshore facilities. The present methodology of the topic is to develop a framework that covers the current market dynamics, operational and maintenance needs of the system, mitigation measures for arising risk factors and technological development of mechanism that generate sustainability and assures financial viability. The approach is to recognize the major asset reliability, integrity, vulnerability, and process safety risks that require detail assessment and evaluation process, to ensure and permit the asset to be operated beyond its design life.

The framework is step forward to figure out some major life extension obstacles by systematic methodology that helps in streamlining the process and provides an improved foundation for pragmatic decision making through four different phases: 1) Detail assessment , history evaluation and decision supportive information collection; 2) Technical assessment and plan for optimization of maintenance needs and operational requirement of the system; 3) Quantifying the uncertainty and prioritizing the risk component or equipment inside of the system; 4) Financial and technical validation of propose model and predictive benchmarking. The developed structured framework provides immense resilience in accommodating a wide and vast spectrum of industry cases.

Acknowledgment

I want to pay my deep respect and profound gratitude to my Faculty Supervisor Jayantha Prasanna Liyanage for his consistent support, motivation, and guidance in the hard time of pandemic. He has been most inspiring and motivating teacher.

I want to pay a bundle of thanks to my external supervisor Dr. Jawad Raza (Business Manager-integrity & Reliability Management at Apply) for providing me the industrial ground for my research work and kind attitude throughout the thesis.

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Table of Contents

List of Figure

List of Table

Abbreviations

AEOL: Anticipated Extended Operating Life

AGV: Automated Guided Vehicle

CoF: Consequences of Failure

EOR: Enhanced Oil Recovery

FMEA: Failure Mode and Effect Analysis

FMECA: Failure Mode and Effect Critical Analysis

FTA: Fault Tree Analysis

HSE: Health safety and Environment

JOA: Joint Operating Agreement

KPI: Key Performance Indicator

LE: Life Extension

MTBF: Mean Time Between Failure

NCS: Norwegian Continental Shelf

NDT: Non-Destructive Technique

NPV: Net Present Value

O&G: Oil and Gas

O&M: Operation and Maintenance

PSA: Petroleum Safety Authority

PW: Produced Water

PoF: Probability of Failure

RUL: Remaining Useful Life

RPN: Risk Priority Number

SAP: System Analysis Program

SCADA: Supervisory Control and Data Acquisition

UT: Ultrasonic Uesting

VDM: Value Driven Maintenance

WI: Water Injection System

1 INTRODUCTION

1.1 BACKGROUND

The oil and gas (O&G) are sophisticated industry with operational activities in almost all continents across the globe. Global oil demand is growing with mixed variable, due to uncertain parameters affecting the supply and demand. The global oil production was 50 million barrel per day before the output cut of 10 million bpd. This output leaded to plunge in demand of 20-25 million bpd because of Pandemic Covd-19 (InternationalEnergyAgency, 2020b). The Figure 1 shows the Global oil demand growth from 2011-2025 with negative curve in 2020 because of uncertain event (Pandemic).

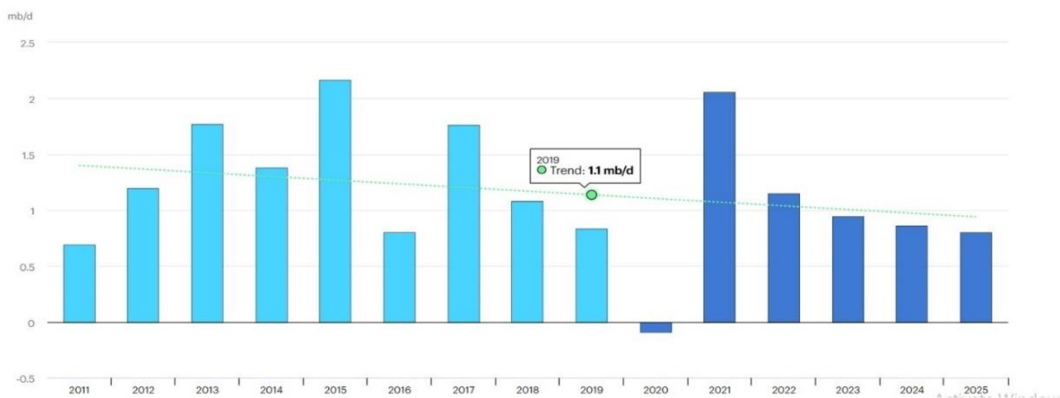


Figure 1: Showing the Global Oil Demand Growth (InternationalEnergyAgency, 2020a)

The history of oil and gas industry in Norway is a saga of rational political decision, magnificent and phenomenal industrial development, and enormous value creation. In a late Feb 1958, the ministry of foreign affairs, Norwegian geological survey had little faith in finding O&G reservoirs in North Continental Shelf (NCS). In 1962 the US oil company Philips Petroleum applied for permit to oversight a geological survey in NCS and later followed by numerous multinational firms (NorskOlje&gas, 2017). In 1965 the treaty was signed between UK and Norway on dividing the continental shelf according to median line principle. On the Eve of Christmas 1969, the US Philips Petroleum informed the Norwegian Government that they had discovered largest ever offshore oil field, named; Ekofisk. Later it came on stream in 1971 and career for Norway as an Oil producer nation started (NorskOlje&gas, 2017).

In 1972 the Norwegian Petroleum Directorate (NPD) as an industry regulator developed and Parliament voted on 14 June to establish a STATEOIL as a state-owned Oil company (NorskOlje&gas, 2017). They also adopted "10 Oil commandments" on which the basis for future Norwegian Oil policy decides. In 1974 a giant oil field State fjord found in NCS; this is one of the largest fields also contain gas reservoirs (NorskOlje&gas, 2017).

Norway is one of the fewest countries in the world introduced carbon tax and impose high taxation on carbon emission. In 1991, the Carbon tax were introduced in Norway Petroleum industry to reduce the effect of greenhouses gases. This invigorate and bolster the position of Norway as the world cleanest petroleum producer (NorskOlje&gas, 2017).The Figure 2 shows us the greenhouse gas emission from the petroleum sector. It shows the value from 1998 to 2018 and projected value for 2018-2023. Since 1996 about 1 million ton of CO_2 every year were separated and stored in the subsea formation (NorwegainPetroleumDirectorate, 2020b). This process of separation of CO_2 from natural gas done in Sleipner vest field and from 2019 the same phenomenon started in Utgard field. In short Norway introduced strict measure to stop the carbon emission in the atmosphere.

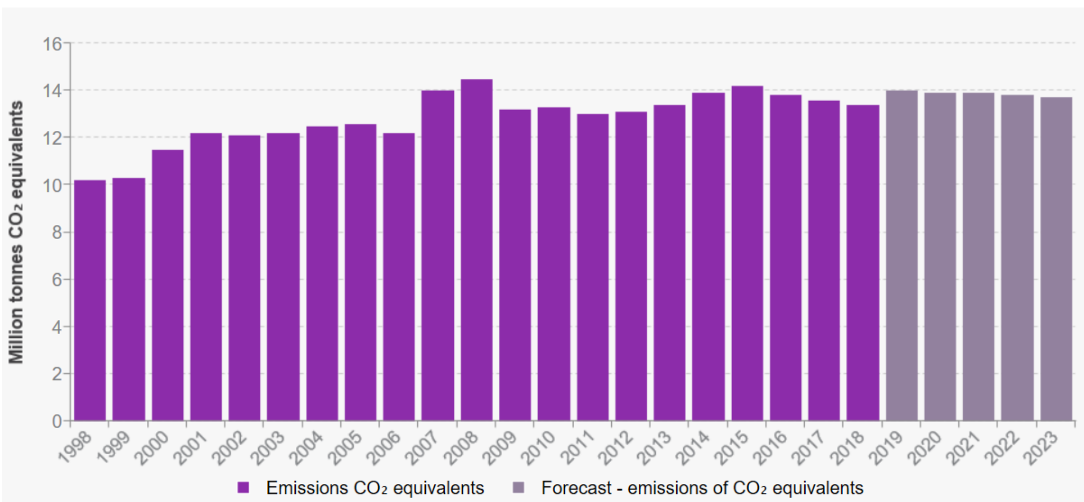


Figure 2: Greenhouse Gas Emission From Petroleum Sector (NorwegianPetroleum, 2020b)

The Norwegian continental shelf covers an area of more than two million square kilometers. The North Sea is the hotspot of Norwegian Petroleum industry with approximately 66 fields which are in production, and more than 19 in Norwegian sea (NorwegianPetroleum, 2020b). The era of black Gold exploration started 45-50 years ago, and later offshore facilities developed. Now most of the fields are working beyond of their original design life by maintaining the safety threshold limits. This is only achievable with the process of Life extension (LE), that mitigates the risk of ageing mechanisms and enhance the life of existing facilities and platforms.

The LE phenomenon also impedes the cost of decommissioning by enhancing and intensifying the operational capabilities of Offshore production facilities. The advancement in technology, modernization and industrial digitalization expedite the working atmosphere. The predictive and prescriptive analytical advancement in operation and maintenance also enhance the life of facilities by maintaining the safety limits. During the process of LE, the integrity management department adopt the new norms of growth and upgrading the platforms and facilities with reliable passage of environmentally sustainable and commercially validated.

1.2 SCOPE AND OBJECTIVE OF THESIS

The scope of the Thesis is to identify important aspects related to maintenance and operations for life extension purposes as an end life management strategy in oil and gas industry. It is thus aimed at developing a Framework taking maintenance needs and operational requirements into consideration. In this Thesis, this is achieved through following objectives.

1. Study the existing practices, processes and published materials for life extension and end life management
2. Identify relevant standards and guidelines and develop the framework to support the specification of maintenance needs and operational requirement of systems.
3. Validate the framework using a demonstration case that helps in future maintenance benchmarking in consideration of Life extension

1.3 METHODOLOGY

The access and approach in this task are to thoroughly study and examine the existing LE practices and their design life methodologies. This comprehensive study comprises of deep understanding of new industry norms and standards, their applications, and implications. The research mode is diversified and expanded, the accessibility to relevant material is mostly will be done through online literature, university library, instructor provided material, Company Apply integrity department inputs and guidelines and applicable advices from the research scholar. The calculation for demonstrated case has been done in MATLAB.

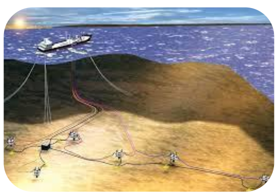
1.4 LIMITATIONS

The LE subject is very broad and comprises of various practices which appears to be in diversified conclusions. Our topic covers the offshore platform and more precisely with collaboration of Apply, it would focus on LE phenomenon with optimization in maintenance strategy inside the system or equipment. The suggested methodology can be applied generally to offshore system or equipment. The structure of thesis essentially covers the NCS, practices, standards and regulation applied in the region.

The validation or comparison of suggested framework with existing models in companies, requires more time and resources**.** Covid-19 hampered the pace of work and access to practical experiences. So, the validation is limited to demonstration case with assumed value and utilization of international standards inside the framework.

1.5 COMPANY APPLY

Apply is a leading multidiscipline engineering company specializing in contracts across all project phases, from concept development and studies to completion and commissioning. It also provides service covering operation and maintenance and modifications of O&G production platform on the NCS. The main Apply business units are maintenance and modification, operational and technical service, and system technology. It also provides flexible rig service, pre operation service and field planning, feasibility service (Apply, 2020). Following are the major disciplines in which apply is providing their service to various companies and successfully executed numerous projects on different fields i.e. Goliat, Gullfak, Ringhorne and Jotun etc (Apply, 2020).



Field planning, feasibility and concept study

Owner Engineering and owner services

Flexible rig service: Classy, modifying and technical support

Specialist consultant study

Digital Operational Solution

Technology and System integration

Modification

Digital Green Service

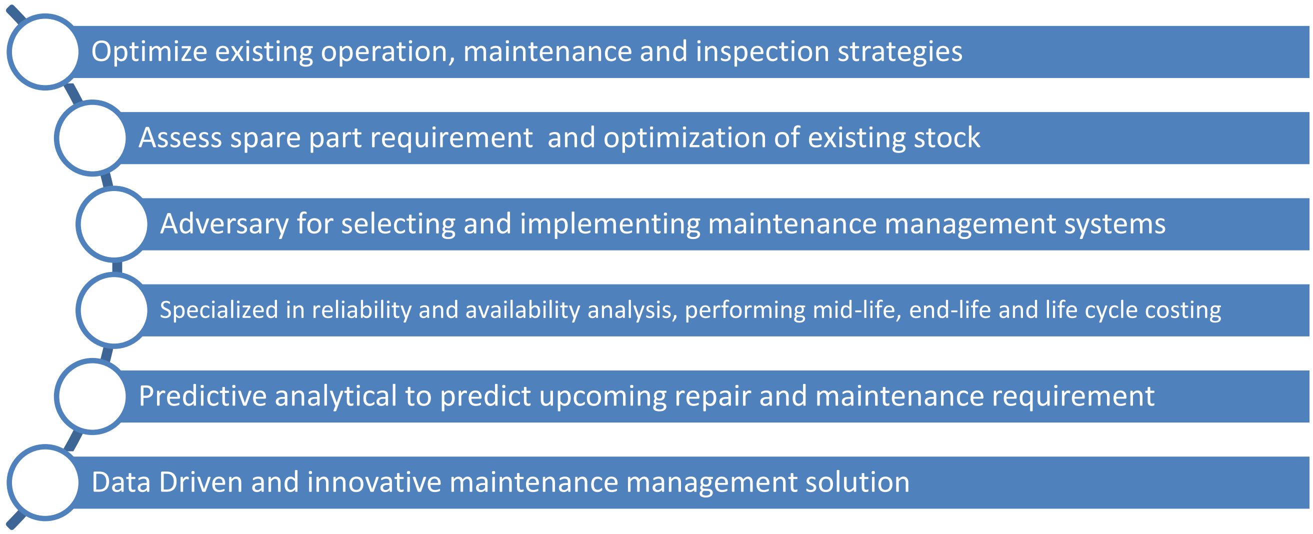
Integrity and Reliability management

Maintenance and Operation support

Marine technical Service

Operations, documentation and training

Apply is helping the customer to achieve the Reliability and integrity targets. They are providing conceptual solution with innovative ideas and thoughts, embedded with experience in various asset management system and strategies (Apply, 2020). Following are the main Integrity and reliability management services provides by Apply



1.6 THESIS FORMATION

This thesis is formulated into four segments:

I. The first section is comprising of introduction part, the thesis classification, limitations, scope of work and introduction about company Apply.
II. The second section is literature review part that consist of current market situation, Norway oil and gas prospect, risk management, production recovery, offshore structure formulations, life extension and ageing mechanisms. The factor affecting the degradation and obsolescence of materials. Boundaries and Pre-requisite for LE and ageing aspects. Major Hazards with their Barrier function and end life management
III. The third section is the suggested framework for LE, in consideration of maintenance needs and operational requirements of system. It also defines the standards and codes applicable in LE process in the region and validate the suggested framework boundaries inside of these standards.
IV. The fourth section is the application of the framework and demonstration case of static pipe equipment with assumed values. All the calculation and simulation will be done in MATLAB with assumed deterioration rate.
V. The last section is the summary, learning outcomes, challenges, and future recommendations.

2 LITERATURE REVIEW

2.1 *OIL AND GAS INDUSTRY OUTLOOK IN NORWAY*

Norway is considered as small impactor in Oil industry while in gas it surpasses Qatar and becomes the largest global exporter after Russia. Norway contributes almost 2% in the global oil production. All O&G produced in Norway are exported and it contributes nearly 50% of the total export of the country. In 50 years since the Petroleum activities started in Norwegian Shelf, it is estimated that only 48 percent of the recoverable resource produced and sold (NorwegianPetroleum, 2020b). Therefore, high amount of reservoir are still left to explore and it is projected that the Petroleum activities will remain high till next 50 years on NCS (NorwegianPetroleum, 2020b). The Figure 3 shows the Oil production history and forecast of the country.

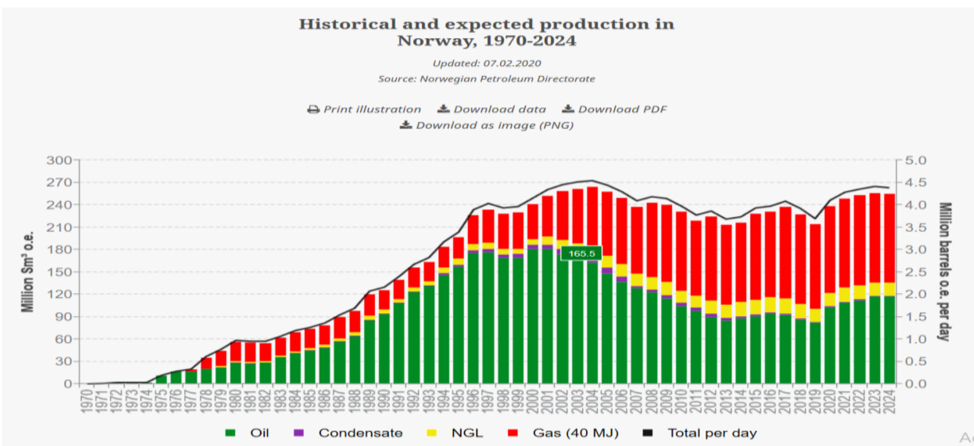


Figure 3: Shows Expected Production in Norway (NorwegianPetroleum, 2020b)

In 2019 the Oil production was counted five percent lower as compared to previous year. The natural decline in mature fields were not remunerate by new fields discoveries, but at the end of the year massive production increased when Johan Sverdrup field started and had positive impact on Production. It is clear evident that without the discovery of new fields or considerable investment in existing fields it may be impossible to enhance the production at current pace in Norwegian Shelf (NorwegianPetroleum, 2020b). The development activities at new fields will compensate the effect of production from the platforms that going through ageing process.

The future production level is vague and uncertain due to pandemic Covid-19 and low oil prices. In consideration of this uncertain atmosphere the Norwegian authority decides to cut the production by 40,000 SM^3 per day in June and 21,000 SM^3 in second half of 2020 while these extraordinary measures will expire at the end of year (NorwegianPetroleum, 2020b). The Figure 4 shows us the total historical production forecast until 2030 assigned by maturity of resources.

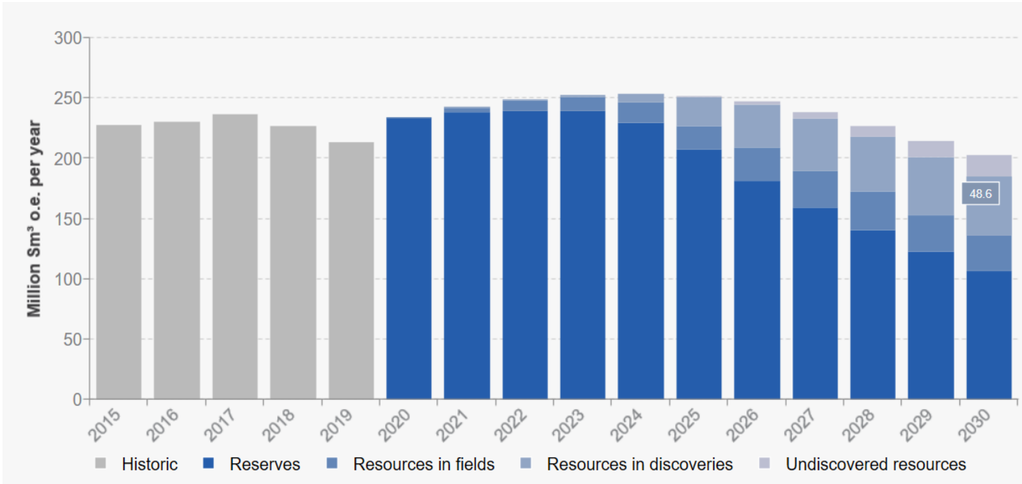


Figure 4: Historical Production Forecast Until 2030 (NorwegianPetroleum, 2020b)

Norway is an important or vital supplier of O&G in the region. About 95% of the gas produced where supplied through subsea pipeline system to all European countries. All the license on the NCS are liable to sell O&G they produce; the exception is only for State Oil company (Equinor) (NorwegianPetroleum, 2020b). The Figure 5 shows us export revenue of O&G in 2019.

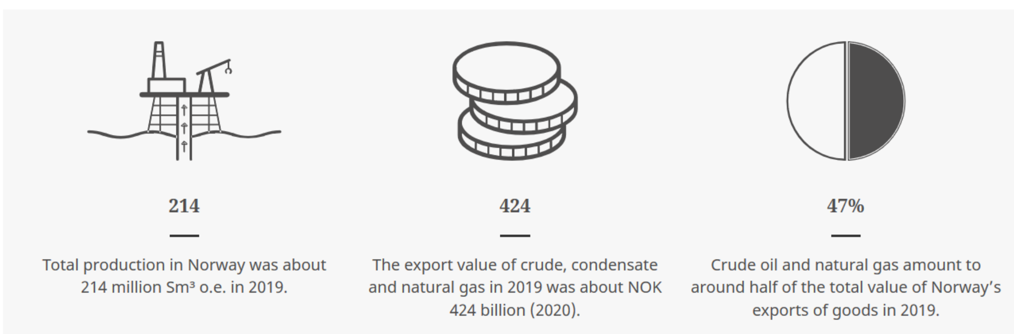


Figure 5: Export Revenue (NorwegianPetroleum, 2020b)

The oil production in Norway reached to climax in 2001 with total liquid production including NGL and condensate was 3.4 million barrel per day. After reaching peak the production decreases until 2013 and onward 2014 the production still increased at gradual pace, with discoveries of new fields and adaptation of advance technology in existing mature fields, that not only increased the production on platforms also enhanced the life of installations and oil facilities. The Norway export of oil accounts 2% of the global oil consumption (NorwegainPetroleumDirectorate, 2020a). The Figure 6 shows the detail global consumption and production of Oil.

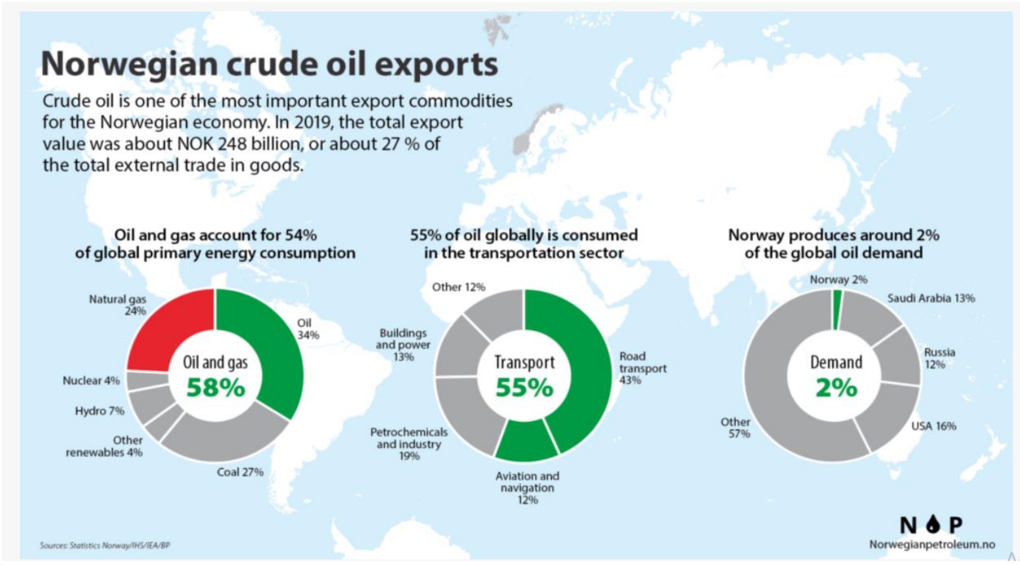


Figure 6: Crude Oil Exports (NorwegianPetroleum, 2020)

The Table 1 shows the sale of crude, NGL and condensate produced in Norwegian Shelf, by first delivery point (NorwegianPetroleum, 2020b).

Table 1: Norwegian Oil Deliveries in 2019, by First Delivery Point (NorwegianPetroleum, 2020b)

First delivery point/country	% of total	Volume (Mill. Sm³)
China	4.5	3.8
Denmark	2.5	2.1
Finland	1.6	1.3
France	3.7	3.1
Germany	7.6	6.4
Ireland	0.7	0.6
Italy	0.9	0.8
Norway	14.8	12.5
Other	2.6	2.2
Spain	2.3	1.9
Sweden	9.5	8.1
The Netherlands	18.8	15.9
United Kingdom	27.7	23.4
USA	2.8	2.3

In Norwegian contental shelf the design life of almost 90% of the facilities have been extended beyond their original calculative life span. Life extensions is a process of extending and refurbishing the life of assets for longer period and assurance of their operational continuity beyond original design limits. It includes the process of extensive studying of assets and their thorough evaluation which propose refurbishment and replacement of assets. In O&G the life extension is economically and commercially proven mechanism and practice that enhance the life of offshore facility when their fields are still effective. The offshore platforms and floating units are built to last but the utmost and acute weather condition, expedite wear and tear; that force the units to structural damage (SolutionMarine&Offshore, 2020). In first quarter of March 2020 State Oil company of Norway, Equinor has finalized to extend the life of more than eight different platform in North Sea, shown in the Table 2 below.

Table 2: Shows Platforms Extended Life (Equinor, 2020)

Installation	Original lifetime	New lifetime	Years of extension
Gullfaks A	**2016**	**2036**	**20**
Gullfaks B	**2017**	**2036**	**19**
Gullfaks C	**2019**	**2036**	**17**
Oseberg East	**2018**	**2031**	**13**
Snorre A	**2022**	**2040**	**18**
Snorre B	**2021**	**2040**	**19**
Norne	**2020**	**2036**	**16**

While the statfjord platform is expected to extend by 20 years of their new design life. In this platform it is expected to reduce the carbon emission by 40%. This project is one of the best examples of environmental, economic, and commercial sustainability (NorskOlje&gas, 2020b). The Figure 7 shows the different platform from 1970 to 2020 along their extended life and decommissioning.

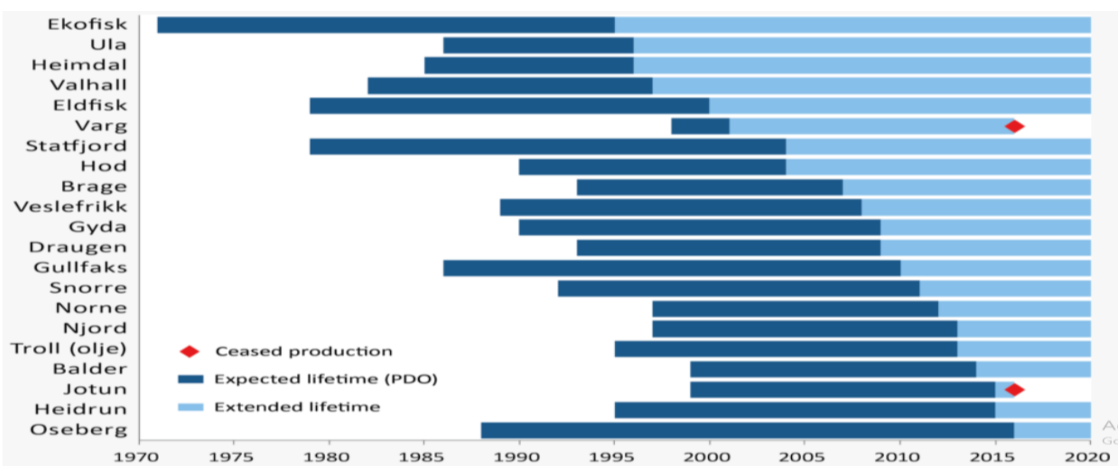
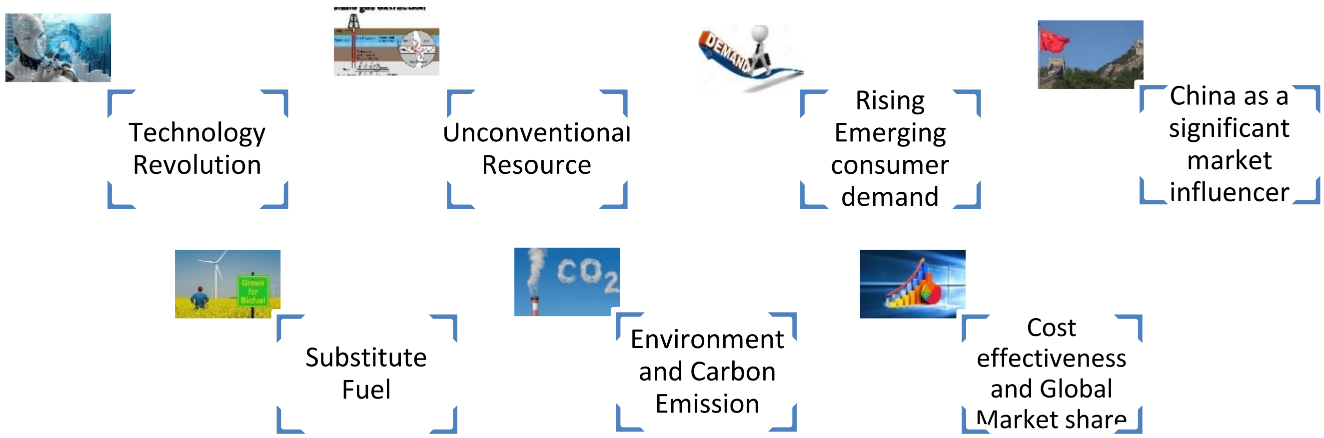


Figure 7: Shows Life Extension of Platform (NorwegianPetroleum, 2020a)

2.2 EMERGING DEMAND AND CHALLENGES

The O&G industry going through enormous and hefty disruption phases. Challenges are everywhere from micro to macro level that are affecting the global industry and economy. The shifting of technology from upstream level to downstream stages, such as refinery operations, infrastructure and petrochemical facilities are gradual and continues (Linchpinseo, 2019). Following below are the few challenges faced by O&G industry globally (Linchpinseo, 2019).



The fluctuating price of Oil is one of the major challenges confront by oil producers' nations and companies. The emergence of new technologies and gradual shifting paradigms towards green energy disrupt the future forecast of Oil industry. The pandemic outbreak, contest to grab the market share, over supply and oil glut in market ,lack of commitments among all oil producers to supply cut and evolution of electric vehicle in the world clumsily upset the outlook of Global Oil Industry (NorskOlje&gas, 2020c). The Figure 8 shows us the energy transition paradigms in transport and chemical sector up to 2035.

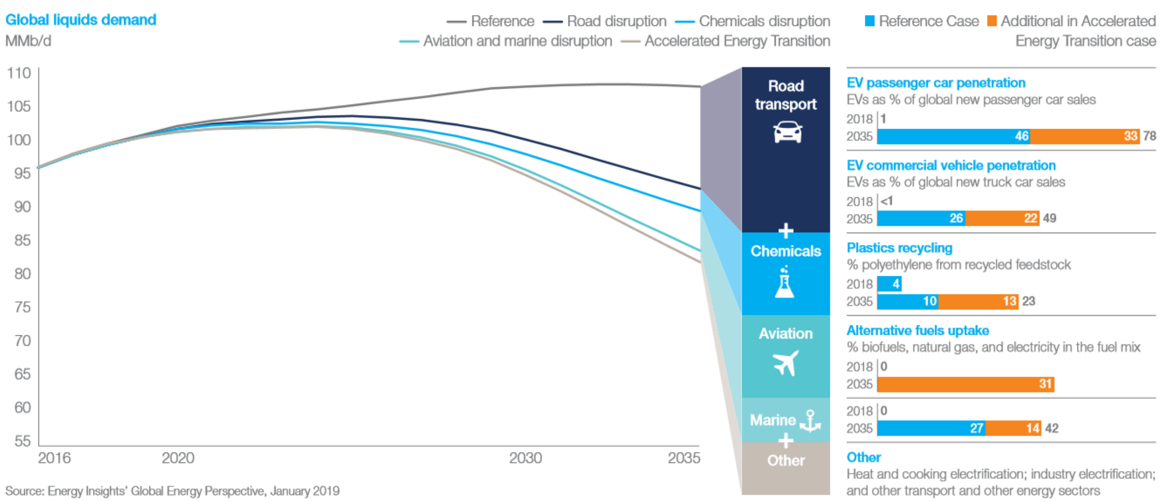


Figure 8: Energy Transition Scenario (Mckinsey, 2019)

Apart from the above challenges faced by oil industry, Norwegian Petroleum corporation experiences extra and further confrontations. One of the reasons is due to their commitment to green energy and becoming role model in the world as one of environmentally friendly oil producing nation. Adhere to reduction in green houses gases and implementation of carbon tax, becoming challenging task in an already packed and competent global oil market. The transformation in world oil market greatly impact the NCS with the crash in oil price and Brent traded below 30$ per barrel. In Norway three project expected to be sanctioned in 2020 with reserves of 269 MMBOE.

The Figure 9 shows the comparison among the revenue, capital, operational and other cost in Norwegian continental shelf in 2020. According to this estimation and computation it is clearly seen that Norway petroleum industry can sustain the price up to 28$ per barrel by covering operational and capital expenditures (EnergyVoice, 2020).

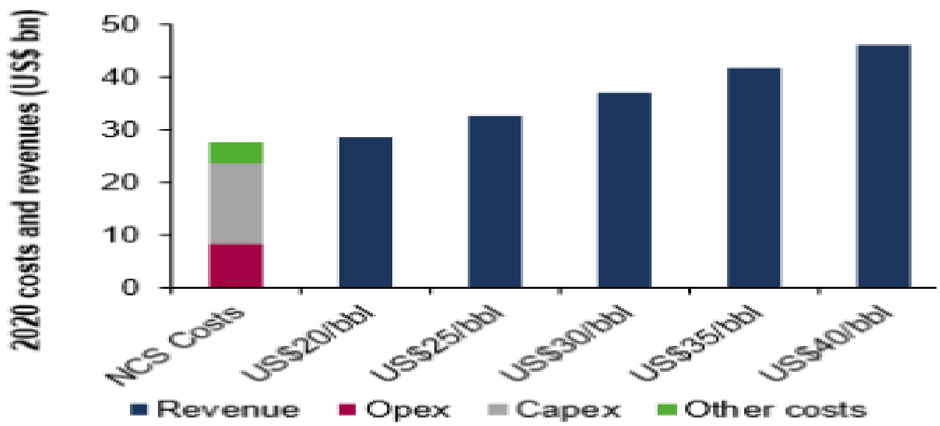


Figure 9: Cost Estimation for 2020 (EnergyVoice, 2020)

The next challenge for Norwegian oil industry may not come from the oil price crash. It seems to be more political and legislative. Norway has temporary ban the petroleum exploration in the region of Lofoten, Vesteralen and Senja Island (OilPrice, 2020).The two biggest parties in Norway, Conservative and labor were in favor of conducting an environmental impact study in these areas. But in recent past the Lofoten chapters of the labor party, currently in opposition and are on friendly term with oil industry now opposing the survey. If labor give in to environmentalist, then next will be Barents Sea (OilPrice, 2020). The Norwegian Petroleum and Energy minister Terje Soviknes told Bloomberg "**If the environmentalist wins this, the focus will quickly move to the Barents Sea** " (OilPrice, 2020)

Johan Sverdrup is Norway's third largest oil field and is supplying energy to the world with one of the lowest offshore drilling costs and with lowest carbon emission (Equinor, 2020). The daily production in phase one is 470,000 barrel per day and it is expected to increase 690,000 barrel per day. It is also noted that CO_2 emission reduced by up to 80-90% and operational drilling cost of the platform is less than 22$ per barrel (Equinor, 2020). This shows the transformation and adaptation of advance technology on NCS which not only ease the production process also reduce the cost in an already packed and competent Oil market. The world energy demands are continuing to rise the exploration of the O&G advances in a significant pattern, but all barrel is not created equal. That is why Johan Sverdrup is prime and glorious example of how the innovation and advance technology make a differ in Global Oil market. The inauguration of this project provides a notable place to Norwegian Petroleum industry in a global world and the commitment of Norway government to green energy (Equinor, 2020).

2.3 RISK FACTORS IN OIL AND GAS

Risks are built-in and implicit in every forward-looking venture. To explore the risk management in O&G industry, extensive and comprehensive framework has been developed. The major risk factors that are considerable in modern day of petroleum industry are Operational risk, financial risk, and Production risk.

2.3.1 ENGINEERING OR OPERATIONAL RISK

In O&G industry, risk is view as a potential element in evaluation of engineering operations and production activities. The engineering exposure includes the risk associated with development, operation and maintenance, construction and exploration, and operating equipment risk (Zhang & Xing, 2011). Sometimes the risk associated to geological activities also fall in engineering category. For example, complexity of petroleum pool, abundance and nature of pool, initial formation pressure, cave, fault condition and active porosity fall in that category. The Figure 10 explains the major engineering risk in petroleum industry (Zhang & Xing, 2011)

Exploration risk

- The inaccurate use of exploration methods, imprecise interpretation of seismic data
- It also cover the improper positioning of exploration well.

Development risk

- It includes the delay in projects, change of engineering design, technical problems associated to development of platform.
- The examples are lack of well control awareness and sometimes formation pressure is too high.

Construction risk

- It covers the loss costs by technical deficiency, un-precedent or unmatched equipment and extension of construction time frame during operational activities.

Operating equipment risk

- The risk associated to operating equipment is improper method of maintenance Instead of applying predictive or preventive maintenance measures ,correctness maintenance approach practices.All the loss of equipment due to hazard and mismanagement includes in this category.

Figure 10: Engineering Risk

2.3.2 ECONOMIC RISK

The fluctuation in external economic atmosphere and ambiguous behavior of financial parameters in current situation hampered economic outlooks of O&G industry. The petroleum related activities have broader geographical distribution, they have long cycle of operation, enterprises and the companies related to O&G industry have large no of employees, keeping in view all these factors, the O&G industry often face economic backlash. They also sometimes face uncertainty in financing, fund turnover, interest, and exchange rate. Tax is a vital tool to control O&G production in the region. In petroleum industry the tax area is expanded from mineral exploration right user fee to mineral compensation resource fee. The tax type is varying from region to region (Zhang & Xing, 2011). In Norway apart from other taxes, the government also added the carbon tax on petroleum related activities.

The O&G industry financial stress will not only dawdle, it is most likely to intensify in coming years due to high volatility in the market. The uncertain scenario in the market and worst effect of pandemic on the oil price, make it least invested commodity in recent months. The difference between supply and demand is widening in negative trajectory. The OPEC+ countries committed to oil output cut in recent past, but it is pre-mature to conclude any fruitful outcome. First time in last 2 decades the Norwegian Petroleum agreed on output cut of 250,000 barrel per day. Now all eyes on the market re-opening and the behaviors of oil importing countries towards to pandemic. The Figure 11 shows us the oil price of last 25 yrs., high volatility can easily be seen, that not only discourage the investor also created high uncertain environment.

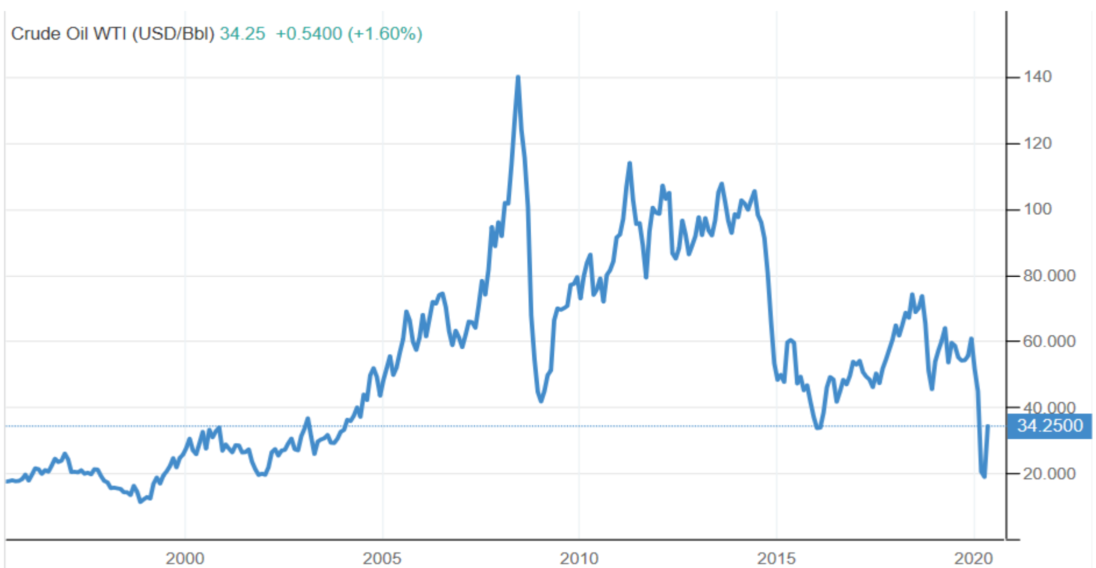


Figure 11: Oil Price Chart (OilPrice, 2020)

2.3.3 MANAGEMENT RISK

The risk originates because of organizations issues, lack of integration among departments, poor quality management, inappropriate methods of health, safety and environment, and impoverished management technique are management risk. Following are the major management risk in O&G industry (Zhang & Xing, 2011).

2.3.3.1 HSE RISK

The risk linked to health, safety and environment have disaster effect on production installation of O&G. Any leakage of hydrocarbon could disturb the whole offshore platform and stop the production (Zhang & Xing, 2011).

The emission of greenhouses gases and affecting the marine life with release of chemical or wastage in the sea. The risk associated to these activities in petroleum industry are the threshold that not only damaging the environment but also in case of hydrocarbon blast it affects the financial, health, life and production installation of platform (Zhang & Xing, 2011).

2.3.3.2 HUMAN RESOURCE RISK

It covers the age composition of employees, their cognitive abilities and adaptation to advancement. The risk links to maintaining the gender balance and multicultural work force is also faced by O&G industry. The professional across the world come to one specific country and gathered at one platform, most of the people are with different ethnic background, with disparate thoughts and attitude. To produce the quality of work and smoothness in execution, complete harmony and integration required. The consensus and cooperation can only nullify and mitigate the risk originates from human resource.

2.3.3.3 ORGANIZATION RISK

It is associated to inappropriate staffing, incoherent sharing of tasks and arbitrary organization mechanism.

It also originates because of versatile attitude of understating in multinational culture. These destitute activities affect the petroleum operation which ultimately leads to enterprise efficiency (Zhang & Xing, 2011).

Risk management is the field that first do deep analysis and then propose and prevent the future risk connected to field and task. It significantly reduces the risk loss and provide remedy to losses. As petroleum operation required high investment and long period, so risk associated to them is usually are very high. To mitigate the risk factor, predictive and preventive measure required instead of corrective action. The Figure 12 illustrate the major strategies and measure required in O&G industry to prevent the risk (Zhang & Xing, 2011).

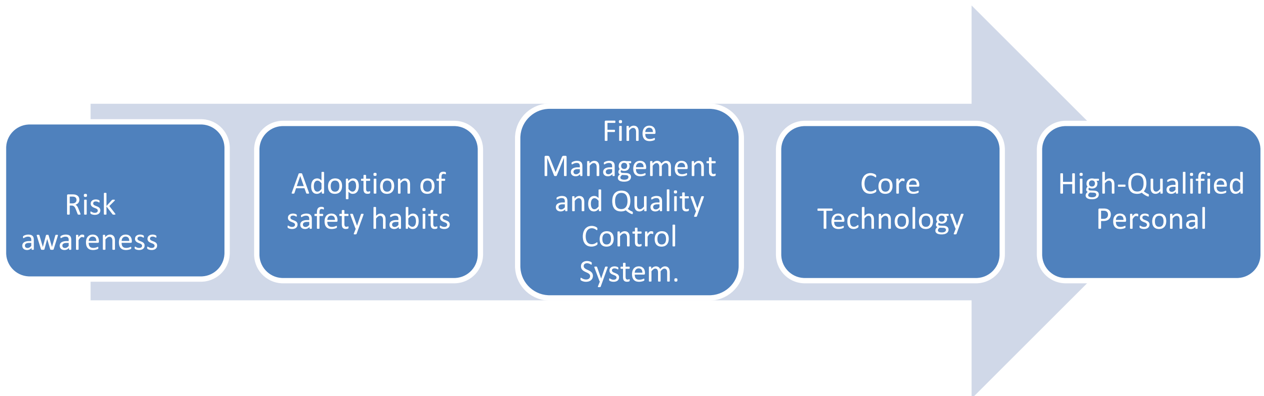


Figure 12: Risk Prevention Strategies

2.4 *PRODUCTION AND RECOVERY*

The production from various O&G platforms and reservoirs consist of different combination of Oil, gas, and water. The mixture of these components has been separated by adopting distinctive techniques and methods. Crude oil is a mixture of various hydrocarbon and formation of these elements in oil vary from field to field (NorwegianPetroleum, 2020b). The quality of oil and their weight depends upon the presence of other substance such as wax and Sulphur. Along the production of crude oil there are mixture of gases also formed such as rich gas or crude natural gas. The rich gas is treated in special refine facility that splits the component of wet and dry gas. The wet gas is also knowing as NGL (Natural gas liquid) while dry gas is methane compound with very small traces of other gases. The NGL is consist of mixture of heavier gases such as ethane, propane, butane, and naphtha) (NorwegianPetroleum, 2020b).

The Figure 13 shows us the annual production of oil, gases, condensate and NGL in NCS.

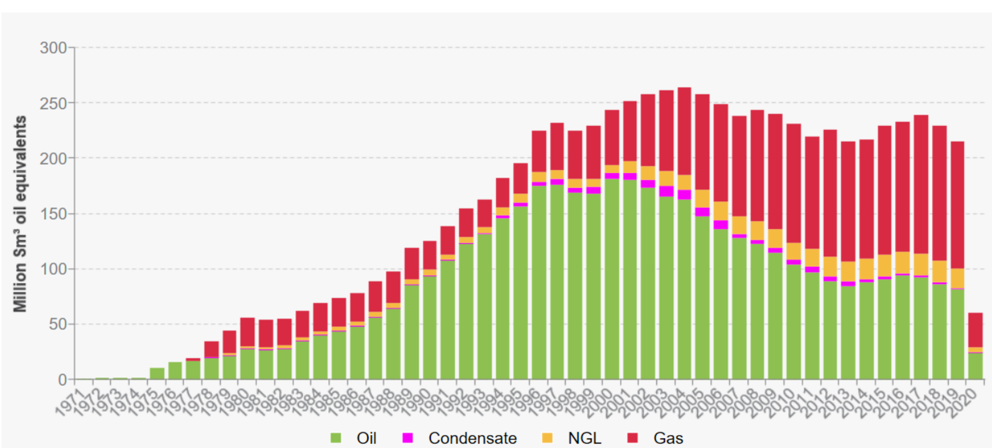


Figure 13: Annual Production of O&G in Norway (NorwegianPetroleum, 2020b)

The Figure 14 shows us the production stages of traditional crude oil project are categories into three different phases (IEA, 2018):

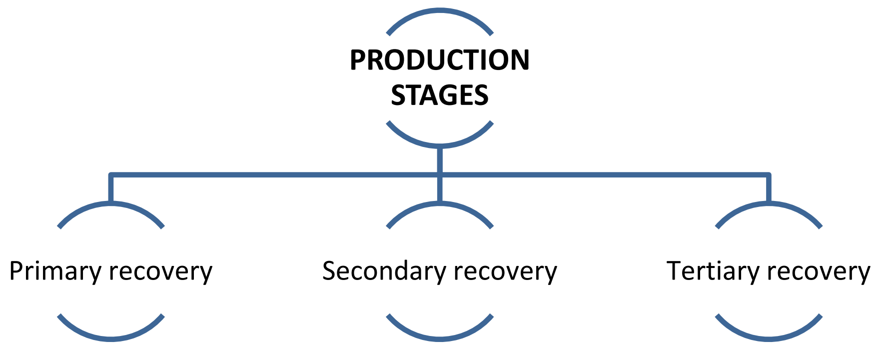


Figure 14: Production Stages

The oil produced in primary recovery is due to natural pressure while in case of secondary recovery pressure in the well is either maintained by injecting water or gases (IEA, 2018). After exercising the second stage of oil recovery, hardly 30% of oil recovered from well. To extract and take out remaining 70% of hydrocarbon the operator adopt the territory recovery method also known as EOR (Enhanced oil recovery) (IEA, 2018).The EOR overturn the falling production of mature field and enhanced the production of oil by reversing the declining curve of aged production facilities. EOR method the recovery rate is usually greater than 60%. The Figure 15 explains the fundamental main classes of EOR (IEA, 2018).

Thermal EOR

- This method is used in heavy oil reservoir.
- It uses the steam to heat the oil ,reducing the viscosity of oil and making it easier for

CO2 EOR

- It is injected into subsurface and then dissolve with oil which increase the mobility of Oil. This process is called as miscible CO2 process .
- In immiscible, the gas doesn't dissolve into the oil, but it pushes the remaining oil.

Chemical EOR

- Water soluble polymer and surfactants are added into water that are injected into subsurface. As it contain high viscosity and pushes more oil out of pores in the oil-bearing formation. The addition of surfactants reduce the surface tension of oil which raise its capability to be displaced by water.

Other EOR

- This category contain all EOR such microbial EOR, in which micro-organism are injected in the reservoir.
- Combustion EOR and other gases injection EOR(similar to CO2 EOR) .

Figure 15: Classes of EOR

Extracting O&G from mature fields require more efforts and thorough planning. The taking out O&G from such reservoir is costly and hectic procedure, so profound and broad mechanism of recovery developed, to extract the maximum oil from well. The Figure 16 shows us the graphical representation of oil recovery techniques at different stages of production. The well production optimization and improved asset recovery are both consider in secondary phase of recovery (Halliburton, 2020).

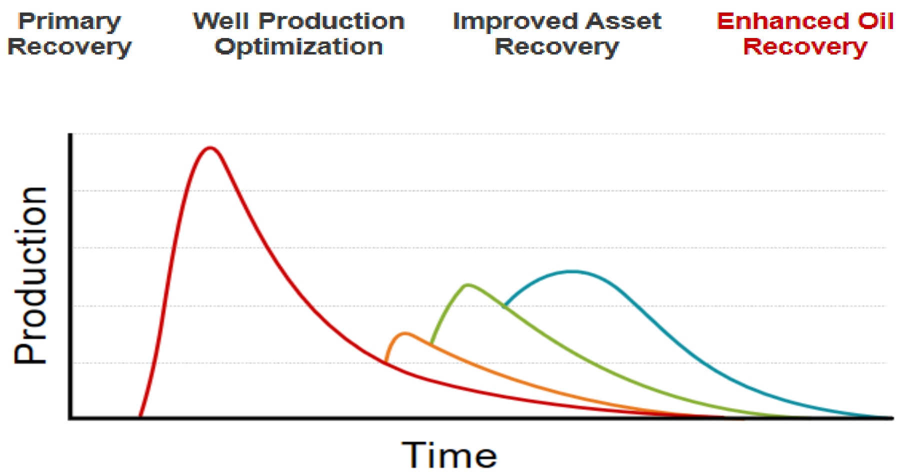


Figure 16: Reservoir Recovery Stages (Halliburton, 2020)

2.5 MATURE FIELDS OR ASSETS

Mature field is that source of hydrocarbon which has already passed the peak of production and is in a declining phase of operation. All hydrocarbon is produced through primary recovery method such as natural pressure. The mature field exist in conventional, unconventional and Deepwater reservoirs (Halliburton, 2020). Mature field also knows as the “brown field” and they are considered as the backbone of O&G industry even though sometime new filed development often take the glare or prominence response in the market. About two third of the oil produced in the world comes from mature fields. The fields are considered as mature if the operational and development life of installed facilities passes 25 years of their design life (Halliburton, 2020).

In NCS, there is number of Oil fields that are in mature chapter of their life and have already produced O&G from their large proportion of existing reserves. Field such as Snorre, Valhall, Grane and Ekofisk still have considerable amount reservoir left, but all these fields are in the category of mature fields whose life is extending beyond their original design (NorwegainPetroleumDirectorate, 2020). Troll is also vital and significant field for Norwegian Oil Production, operational activities continue the site for a long time and it still contain handful amount of reserves (NorwegainPetroleumDirectorate, 2020). The Figure 17 illustrate the remaining proportion of original oil reserves and size of remaining oil reserves. While the size of circle specifies the remaining reserves.

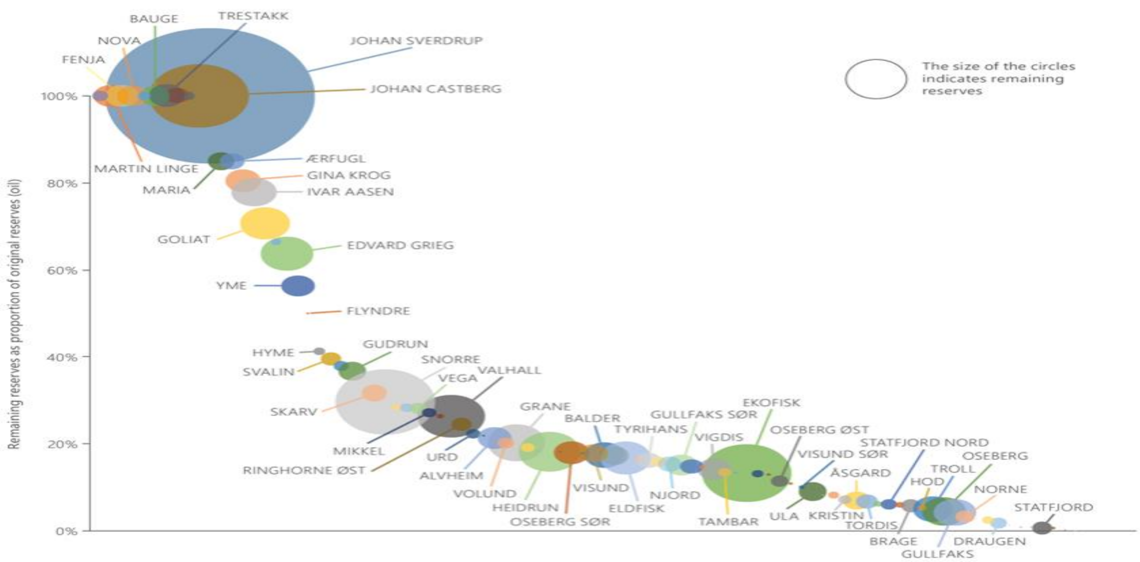


Figure 17: Remaining Proportion of Original Oil Reserves (NorwegainPetroleumDirectorate, 2020)

2.6 AGEING ASSETS

Ageing is the process in which skeletal and functional degrade concentrated and pile up inside of element, component, platform, and any asset installation. The ageing mechanism starts with the initiation of the system life and it grows deeper as the system get old. Sometimes early degradation and deterioration occurs because of poor operation and maintenance planning. Offshore O&G systems are exposed to harsh and severe weather conditions, uncertain storms, and circumstances. To overcome and undo such ambivalent atmosphere, integrity management approach and planning are required (Wintle & Sharp, 2008). The bathtub curve in Figure 18 shows three different phases of system life. The initial start is burn out phase with very high failure rate, then there is useful period of life with constant failure rate, and at the end the wear out and deterioration period approaches. In O&G operation the early burnout phase is mostly discarded but in context to LE, there is a need to develop mechanism that defer depreciation period or mitigate the effect of ageing. Also, during the period of constant failure rate, appropriate maintenance, and legitimate operational planning will curtail and scale down the effect of devaluation with respect to time.

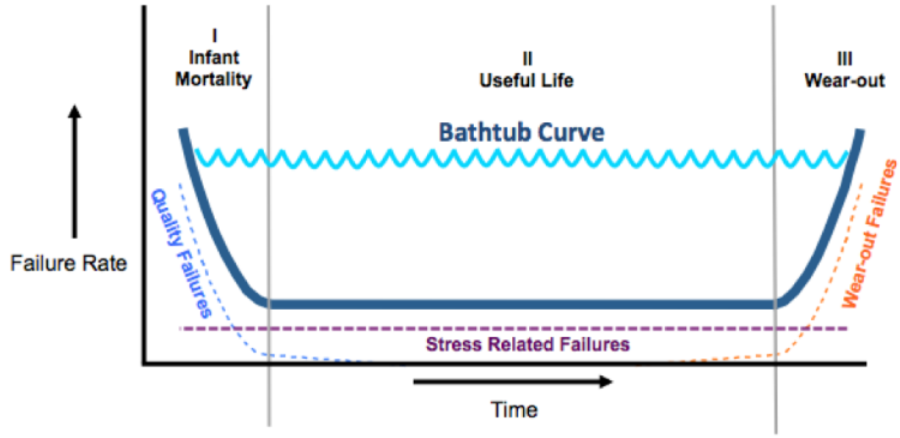


Figure 18: Bathtub Curve (ApexRidgeReliability, 2015)

2.6.1 AGEING MAINFRAME

Ageing process is wider and multidimensional subject. It comprises of numerous sections and aspects, but it is divided into following three primary and considerable chapters. The Figure 19 shows us the three sections of ageing mainframe.

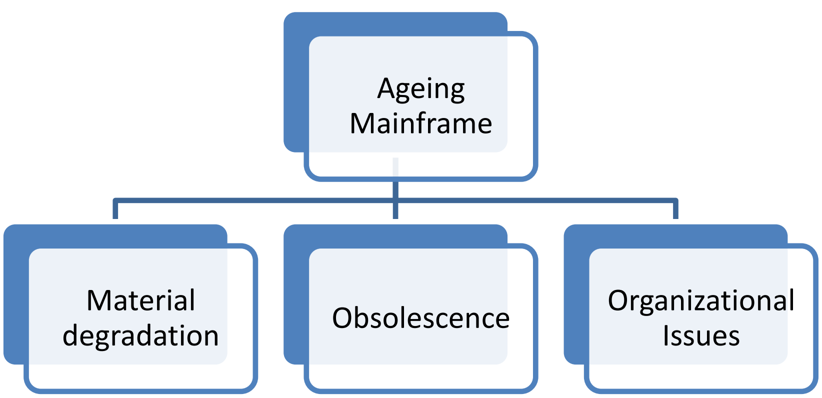


Figure 19: Ageing Mainframe

2.6.1.1 MATERIAL OR PHYSICAL DEGRADATION

The material degradation is a chemical process that occurs mostly due to oxidation in dry atmosphere, while wet environment contributed to the form of corrosion. Also, sometime due to metallurgical process, physical degradation of material and substance occurs. The harmful effect on the life of material is seen either in term of softening of substance or embrittlement (AndreasHugaas, 2006).

The Figure 20 summarize the prospective corrosion mechanisms at NCS in O&G production installations and equipment, which are exposed to harsh and uncertain environmental conditions.

Corrosion Mechanism	*External*	*Internal*	*Chemical reaction*	*Time dependency*
O_2-corrosion	X	X	$2Fe + H_2O + 3/2O_2 \rightarrow 2FeO(OH)(s)$ ("rust")	Time dependent
CO_2-corrosion [1)] (sweet corrosion)	NA	X	$Fe + H_2O + CO_2 \rightarrow FeCO_3(s) + H_2$	Time dependent
Microbiologically induced corrosion (MIC)	X	X	Fe + "bacteria related oxidant" $\rightarrow Fe^{2+}$	Time dependent/ abrupt nature
Sulphide stress cracking (SSC) (corrosion due to H_2S)	NA[2)]	X	$2H+ \rightarrow H\cdot(ads)$ $H\cdot(ads) \rightarrow H_2(ads)$ (inhibited by H_2S) $H\cdot(ads) \rightarrow H\cdot(abs)$	Abrupt nature

[1)] Not anticipated on corrosion resistant alloys

[2)] Under certain conditions high levels of H_2S might occur in the seabed, however, such condition is not anticipated to occur on the Norwegian shelf.

Figure 20: External and Internal Corrosion Mechanism in a Subsea O&G Production Environment (AndreasHugaas, 2006)

The physical degradation of substance depends upon their maintenance practices, operational condition, and the properties of material. Few of the degradation mechanisms are due to fatigue and metal loss which are purely time dependent events.

2.6.1.2 OBSOLESCENCE

A component is "Obsolete" only when it can no longer be procured and when it will be impossible to replace failed substance with new one. It also refers to the period when manufacturer may stop and abandon fabrication or production of specific substance due to unforeseen reasons. In O&G industry the obsolescence's are mostly defined as the hardship or struggle that is faced by the supplier in supplying new component of existing model (Hokstad, Haabrekke, Johnsen, & Sangesland, 2010). The difficulty in adoption of modernization and digitalization of traditional and conventional practices of drilling also considered as "Obsolescence".

2.6.1.3 HUMAN FACTOR AND ORGANIZATION

An industrial asset is a segment of an organization and it works under the framework of organizational architecture and subject to effect by change in intrinsic behavior of human resource. The advancement in drilling technologies and evolution of digitalization over the period is unprecedent. While the ageing workforce are mostly reluctant to adaptation of such modernization. An industrial asset is basic component and part of management system and organization, so any fluctuation in institutional structure and human factor will affect the asset growth and expansion. During the process of LE, steps should be taken in consideration of these two aspects: Human factor and organization (Hokstad et al., 2010). The Figure 21 illustrate few primary issues faced by organizations because of ageing mechanism.

Figure 21: Organization Issues Related to Ageing Mechanism

2.6.2 AGEING MECHANISM AND EFFECTS

Retaining and sustaining the support of alertness and realization of ageing mechanism is one of the major challenges faced by operators in O&G industry. With the passage of time, the operational condition of system and equipment's may fluctuate from their model design intent. In NCS or North Sea offshore installations, the environmental standards for emissions and waste have become progressively more rigorous and sever over the time. The existing design of equipment and plants may not meet the modern norms and standards (Wintle & Sharp, 2008). So, during the process of LE, a comprehensive integrated solution should be developed that meets the requirement and needs of modern norms and standards.

The Figure 22 shows us that ageing mechanism divided into three different divisions.

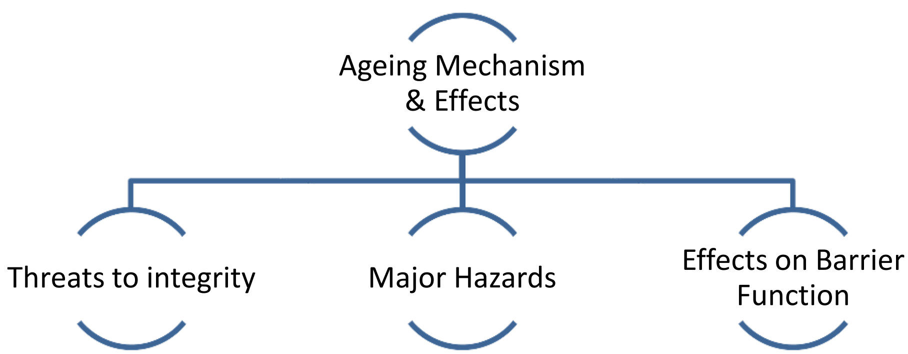


Figure 22: Ageing Mechanism

2.6.2.1 THREATS TO INTEGRITY

In offshore production installation as time passes, numerous threats to integrity originates and expands from physical degradation to obsolescence. Following below few nominated threats are mentioned along with their effect of ageing mechanism (Wintle & Sharp, 2008), as shown in Figure 23.

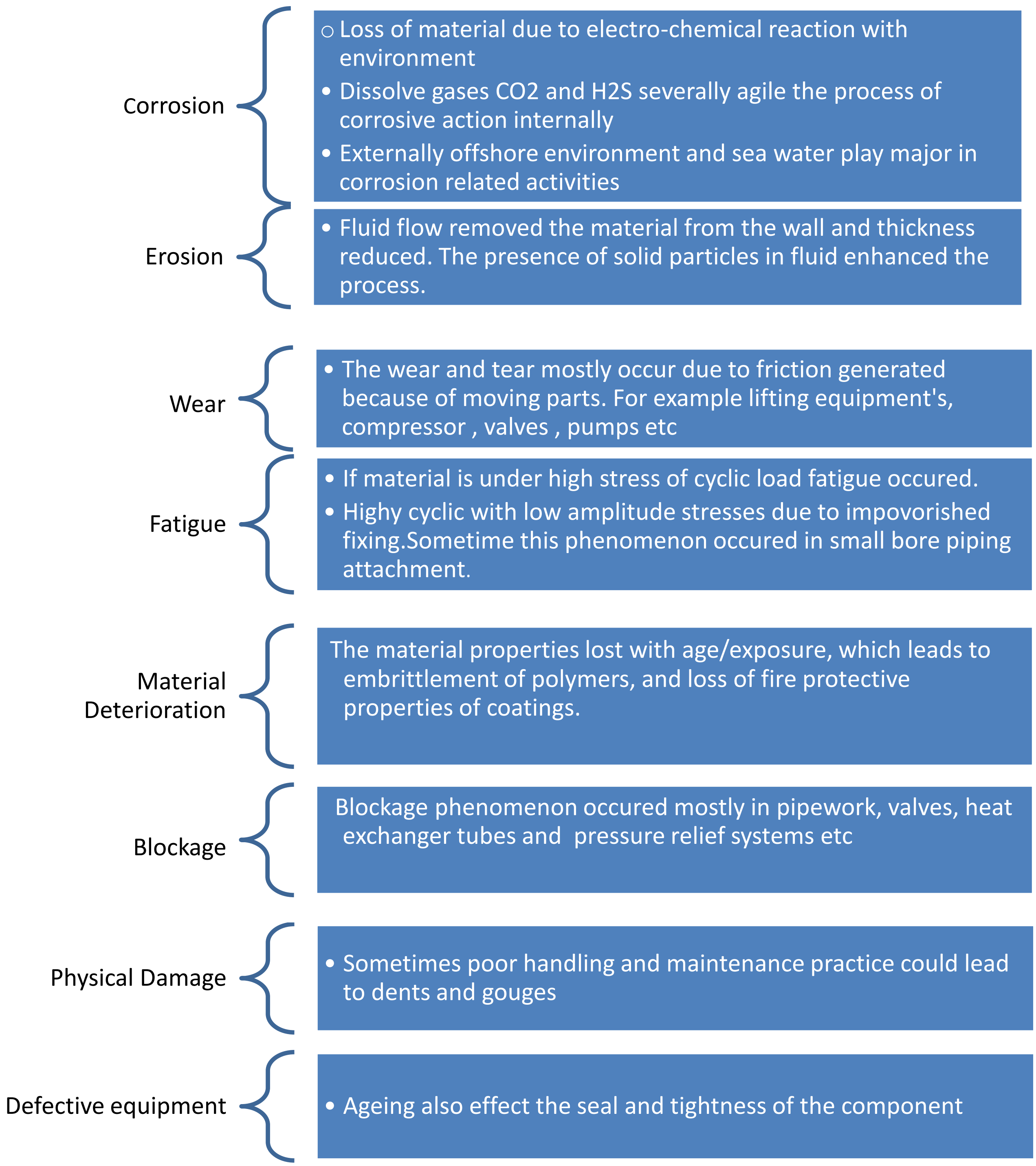


Figure 23: Threats to Integrity

2.6.2.2 MAJOR HAZARDS

In offshore O&G platforms there are some major hazards with respective to their functional barriers. Mostly the ageing mechanism severely effect these functional barriers that leads to disasters event and crudely effect the trial and technique of LE. In a conventional offshore O&G production installation, there are several major hazards competent and qualified for generating a genuine risk to personal and equipment's (Wintle & Sharp, 2008). The ageing process enhance the probability of such incident, this could only be reduced and dumped by integrity and reliable counter efforts in term of LE measures. The Table 3 shows us few major hazards and their system barrier in Offshore O&G installation (Wintle & Sharp, 2008).

Table 3: Major Hazard and Effects of Ageing Process (Wintle & Sharp, 2008)

S/NO	MAJOR HAZARDS	RAMIFICATIONS	EFFECTS OF AGEING MECHANISM
01	Hydrocarbon (HC) leaks	Shut down, loss of Production, asphyxiation	Over 60% leaks on HC system are caused by ageing mechanism such as fatigue, corrosion, and erosion etc.
02	Fire and explosion	Reduce safety of personal, damage to equipment, loss of production and structural failure, collapse, and escalation	Reduced sensitivity of gas, smoke, and fire detectors with age due to poisoning of sensor, mechanical damage, window deterioration (in infra-red detectors). Reduced pumping rates and leakage of active and passive fire systems.
04	Structural collapse of top side and Top side equipment	Damage to safety critical systems, pipe rupture, HC leaks, loss of escape and rescue capability and routes.	Fatigue and corrosion of structural steelwork can reduce load carrying capacity
05	Failure of evacuation, escape and rescue system (EER)	Risks to safety of personnel following an event	Corrosion and fatigue can cause reduced integrity/collapse EER system (Walkways, mooring etc.)
06	Human Factor	Increased risk of other major hazards	Over familiarity with equipment can reduce awareness ageing effects and leads to maintenance backlogs.

2.6.2.3 *EFFECTS ON BARRIER FUNCTION*

Barriers are mostly defined and stated as any organizational, institutional, technological, and operational measures that impede or mitigate the effect of calamity and failure. Ageing badly effect the operational and technical capabilities of barrier and their functionality (Wintle & Sharp, 2008). In Table 4 numerous technical barrier functions along with the adversity of ageing mechanism is describes

Table 4: Barrier Functions and Ageing Process (Wintle & Sharp, 2008)

S/No	DESCRIPTION	BARRIER FUNCTION	AGEING MECHANISM
01	Material Selection	Mitigate the risk to hydrocarbon leaks and enhanced the protection against fire.	Material degradation
02	Corrosion Protection design	Reduce the effect of corrosion and their vulnerability	Corrosion protection system with reduced performance due to ageing processes.
03	Fatigue design	Defiance to fatigue and diminished the effect of HC leaks	Fatigue processes accelerating due to ageing, leading to vibration and HC leakage.
04	Inspection and maintenance	Reducing the risk of HC leaks occurring and to maintain the resistance to fire and explosion through regular in-service inspection and maintenance (IMR)	Lack of sufficient IMR to meet ageing requirements.
05	Gas detection	Decreased the adversary of HC leaks and mitigating the risk of fire and explosion	Ageing process degraded the gas detectors
08	Blast Walls	Constraining the extent of an explosion and protect the critical equipment and personal	Supports for blast walls deteriorating due to corrosion
09	EER facilities	Enable the orderly evacuation from the installation in case of emergency, outbreak, and rescue facilities.	Performance of EER facilities loss or reduced due to ageing phenomenon

2.7 REMAINING USEFUL LIFE (RUL)

In LE process, the remaining useful life (RUL) is detrimental factor to exactly quantify the life of an asset. The RUL is the remaining useful life left of any asset, platform, and installation at an appropriate time of an operation. RUL is instinctive assessment of the number of remaining years that an element, feature, thing, structure, and system is estimated to be able to operate in synchronization with its predetermined purpose before warranty restoration (RemiAl, 2019). Its evaluation is pivoted to condition based monitoring, predictive maintenance, prognostics, and health management. The Figure 24 shows us the generally asset deterioration profile.

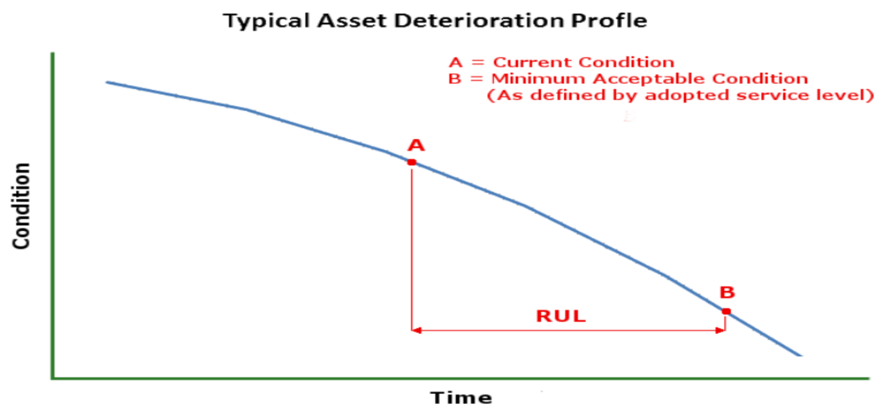


Figure 24: Asset Degradation Profile (RemiAl, 2019)

In above graph point "A" shows the current condition and point "B" shows the failure condition. This is typically machine deterioration profile and RUL can be calculated in number of days, weeks, months, and years, depending upon which scale the operator use (letter, 2020). There are three common patterns to calculate RUL, depending upon the machine or asset profile, their uses, failure modes and accessible to failure history. These patterns are described in Figure 25.

Similarity Model

- This model also knows as run to failure data model. If there is data from identical item or various component showing related behavior , then this model can be used to estimate RUL of assets.
- This model is used when there are run to failure histories from similar machinries

Survival Model

- It is also known as lifetime data model. Proportional hazard models and probability distribution of component failure times are used to estimate RUL from the lifetime data.
- This model is commonly used when there are failure data from similar machineiries

Degradation Model

- This model connected to the threshold of failure. Mostly used when the indicators of failure limits are known.
- The threshold data model used principle component analysis to estimate RUL of any asset.

Figure 25: RUL Calculating Model

2.8 END LIFE MANAGEMENT

The end life management of any asset can be improved through the application of advanced dynamic analysis. When the equipment or system get old, there is a systematic approach in all industry either keep using the same equipment, replace it with upgraded model or enhanced the existing capability of the system. In O&G industry end of life assessed via various models and then thorough framework developed to manage the end life of system. In end life management of O&G industry, mostly operator has following two option:

1) Decommissioning
2) Life Extension

2.8.1 CESSATION AND DECOMMISSIOING

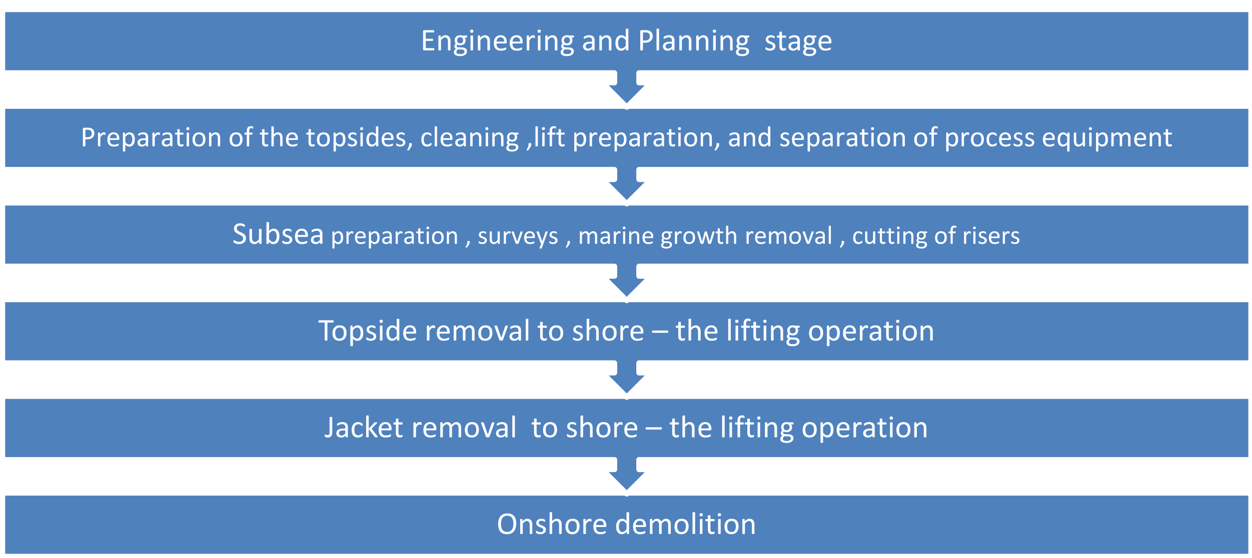
Decommissioning is the process comprises of eradication of industrial installation, production facilities and structural platform that has come to end of their productive life period. In offshore O&G industry the decommissioning process consist of several stages, started from well securing operation subsequently leads to structure and pipe joining the platform would be removed. (SalinoImregilo, 2016). To make the cessation process sustainable and environmentally friendly, adequate and possible site for storage of non-usable material and polluting elements such as metallic and plastic wrecks must be identified (SalinoImregilo, 2016).

The decommissioning principle is distinct from the installation mechanism of platforms and production facilities, it is unglamorous project and end of field life. The elimination and removal of redundant material from the site have links to the reputation of the owner and regional head. The Figure 26 explains that decommissioning process comprises of following main interrelated/analogous issues.

Figure 26: Interrelated Issues of Decommissioning Process

The decommissioning operates worldwide under strict UN regulation, govern by International Maritime Organization. It mostly requires complete removal of platforms and installation in less than 100 meters of water but also allowed the structural eradication to beyond -55m of depth. The rules and regulation varied from region to region. As in North Sea it is prohibited to dispose of any material in the ocean. The national laws of environmental protection show the national interest of the country.

In offshore cessation and decommissioning process there are following six stages in complete wrap up and removal of installations and production facilities.



The Figure 27 elaborate the four major factor on which decision to do decommissioning and cessation depends:

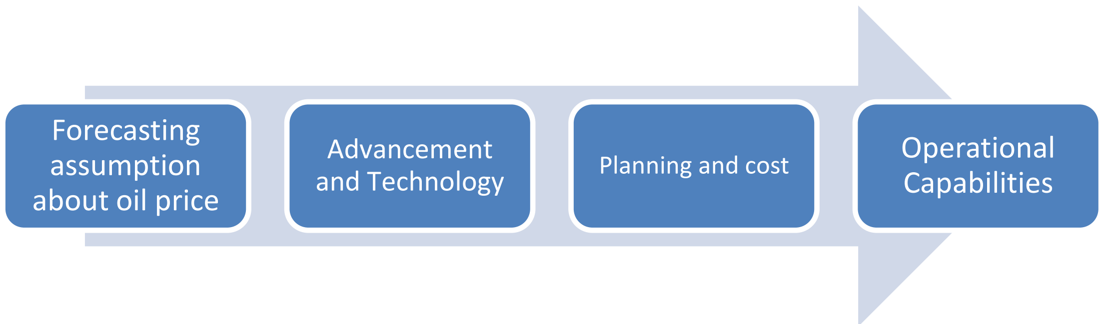


Figure 27: Decommissioning Decision

The decommissioning phenomenon is supported by following two main decisive model:

1) Environmental
2) Financial Model

2.9 LIFE EXTENSION

The main idea of LE is to extend the life of certain platforms or installation when they are due for retirement, this can be done by adopting critical approach and criteria's, in this way the life of that installation can be enhanced without affecting the safety limits. In O&G industry the design life of equipment's are mostly ranged for 20-25 years (SolutionMarine&Offshore, 2020). This limit is defined by the manufacturer's expertise. The enhancement in life of equipment conventionally interdependent on the level of maintenance, operational modes, and type of refurbishment. But more radical steps in process of LE could upheld the change required in integrity management, accessing the design life of equipment, and prescribing the LE proposal in consideration of safety limits.

The main edge of LE during the procedural process, is that it may point out new failure mode that was not evident during the original design life. It is the moment and time to reset the clock and address the maintenance and surveillance backlogs. LE is the process of good routine management, and it establishes new inspection modes and boosts duty holders. It also contains an element of independency from installation team which leads to impartial view for ageing of equipment's (Wintle & Sharp, 2008). The LE is an ideal time to reconsider and re-evaluate the integrity management systems and manpower essentially required to regulate the ageing machinery. The inspection and maintenances interval, craft capabilities and performances, erosion and rust, data management history and weariness/fatigue management programs all can be refreshed and rejuvenate (Wintle & Sharp, 2008).

Automation and engineering modernization in asset life extension have compel the O&G industry to rely on their platforms longer than their original design life tenure. There are four key areas which must be followed by operators during the process of asset life extension, which are given in the Figure 28 below (Claxton, 2020).

Figure 28: Four Key Areas in ALE

The LE is integrative process enters in different aspects that intervene during the life period of platform and existing facilities, their operational sustainable environmental condition and their financial prospect and business endorsement. Therefore, it is evident that such scrutiny and analysis must examine various criteria such as availability, capability, profitability, reliability, and business validation.

The LE process and management are an integrity approach and have interconnectivity with all other existing departments and programs. The Figure 29 shows us the detail relationship of Ageing and LE management with other relevant scheme and procedures.

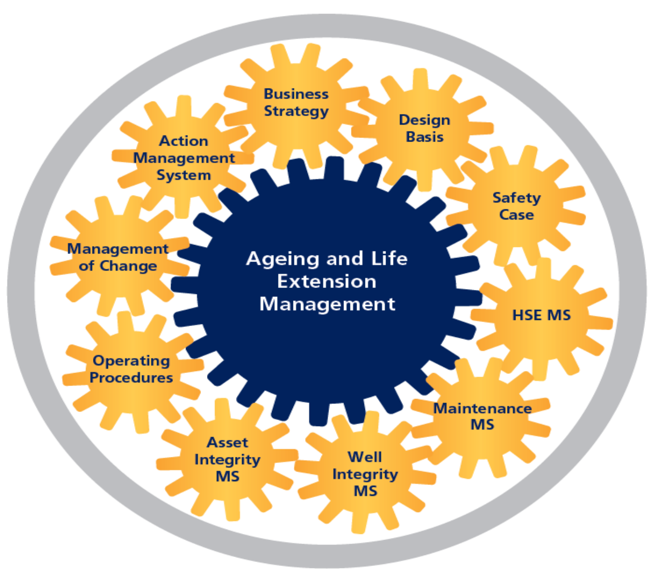


Figure 29: Main Element of LE and Ageing Management (Oil&GasUK, 2012)

2.9.1 POTENTIAL DECISION INFLUENCE FACTORS ON LIFE EXTENSION

In O&G sector with passage of time the structural integrity and equipment maintainability reduces and becomes victim of ageing mechanism. Most of the facilities and platform in offshore are design for life span of 20-25 years. This lifetime is subjected to high maintainability, producibility and timely service of equipment's. Enhancement in the lifetime of platform could be possible by timely inspection, upgrading, replacing faulting machinery and equipment and proper maintenance. The risk of ageing mechanism could be mitigated by adopting condition monitoring approach with predictive analytical behavior and thoughts. The idea of life extension is to adopt such measure and criteria that enhance the life of offshore platform without damaging the safety limits. In Norway, when companies are considering extending the life of platform beyond their design limits, they are supposed to apply to Petroleum Safety Authority Norway (PSA) for consent (NorwegianPetroleum, 2020b). The PSA is the highest authority to authorize extension procedure. Following below are the certain factors and boundaries for LE.

1) Remaining Prospect in the Reservoir
2) Investment and Cost
3) Advance technology
4) Environmental Sustainability
5) Safety Integrity

2.9.1.1 REMAINING PROSPECT IN THE RESERVOIR

The field LE process is an excellent method of managing resource, as it leads to value creation from existing and established fields. Before the start of LE process, there are boundary limits under which LE phenomenon can occur which includes the assessment of reservoir and their economic prospect in a competent world of energy. The prediction of remaining reservoir of field is pre-requisite for initiating the assessment procedure of LE. Without the accurate quantification of remaining reservoir and their economic and environmental viability, LE process cannot be started. Remaining prospect of reservoir should be validated economically and their accessibility to field.

In NCS, the Statfjord platform is one of the prime examples of LE implementation. Previously there was a plan of decommissioning the field by 2022 but then later Equinor and their partner identify the area and develop a plan to extend the life of platform by 2040.There were enough reservoir in the field and prospect of these reservoir were economically encouraging. The startfjord field earned more than 1600 billion NOK to Norwegian government (Equinor, 2020). The new business plan ensures higher use of resources in consideration of all the segments of

LE i.e. safety integrity, technology synchronization, reducing carbon emission, adoption of advance technology and techniques.

2.9.1.2 INVESTMENT AND COST

Now currently the oil price is trading below 20$ per barrel due to lockdown (Covid-19) and high uncertain atmosphere (TradingEconomics, 2020). In such an unclear environment the investors will be very reluctant to explore new rigs and wells. Either they would prefer to enhance the life of existing platform by reducing cost of infrastructure and exploration. So, LE is one of the economically viable option and companies prefer to adopt this channel. Companies and industries will use new and different technologies to extract the remaining oil that they cannot produce by using available technologies. This will be more cost- effective rather than looking for new reservoirs and building new platforms. The Figure 30 shows the fluctuating oil price.

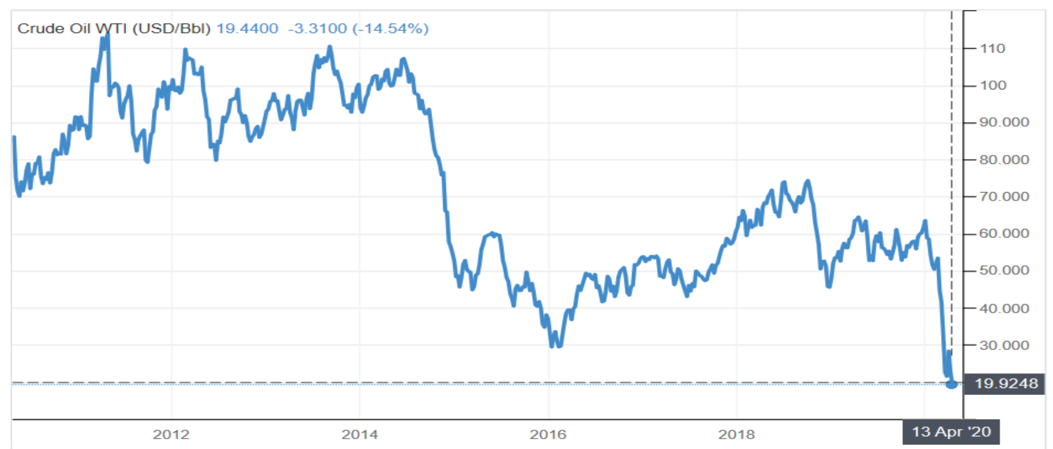


Figure 30: Crude Oil price forecast (TradingEconomics, 2020)

2.9.1.3 ADVANCEMENT IN TECHNOLOGY

This is considerable thought that average recovery of O&G from reservoirs are about to 35-40% of their total value. In order to maximize the output and to extract the remaining reserve from the reservoir new technologies has been introduced (Hummes et al., 2012). The Figure 31 shows some high technologies plays an important role in life extension of the platform by maximizing the output and mitigating the risk of ageing. By using such technology, it is inevitable to extend the life of existing facilities.

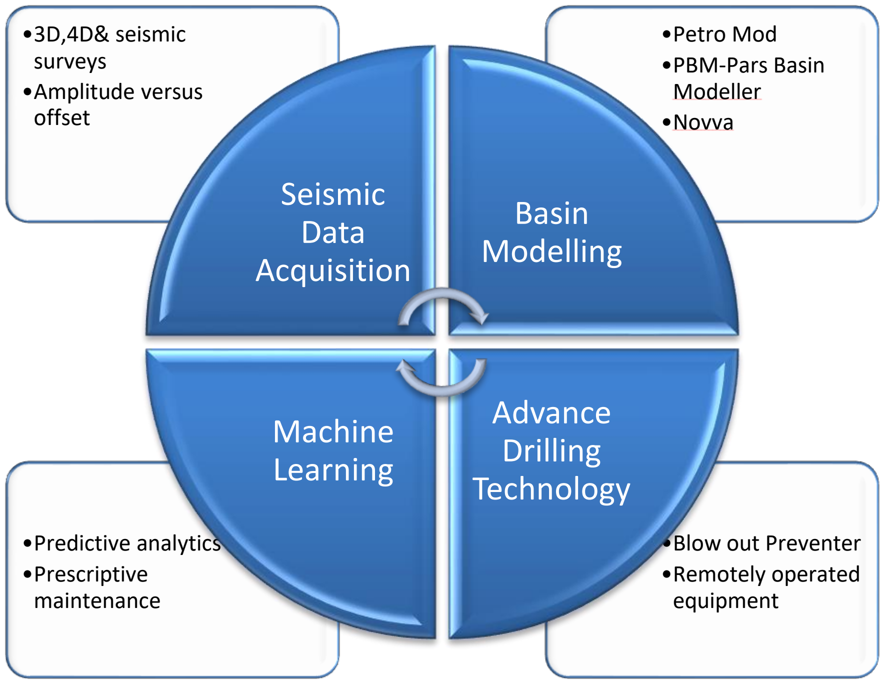


Figure 31: Advance Technologies

O&G industry is adopting new era of low oil pricing, oversupply, and technical complexity. The industry is at state of disruption, facing new set of challenges, as they look to realize cost efficiency in their project and operations, while maintaining safety and reliability. The latest digital technology enables the operator to quickly respond to opportunities and challenges. BIGDATA is increasingly available for every aspect of drilling, production, operation and maintenance (BobDudley, 2015). By using cognitive analytical solution, the operators can take better decision, cut down on risk and ensure efficient use of resources. Digital technology allows the O&G industry to predict incident before it will happen, enhance maintenance, operation, and mitigate weather risk (BobDudley, 2015). Digitalization pave the way for processes simplification and automation technology, that are redefining reservoir management, drilling processes, increasing the speed and safety of drilling operastion.BY adopting these technologies operation and maintenance will be monitored and optimized around the clock in synchronization of system integrity and reliability. Pipeline integrity will also be enhanced through sensors and autonomous underwater aerial vehicles equipped with sophisticated sensor system and cameras (BobDudley, 2015).

Digital technologies united with data driven insights will revolutionize operation, enhance efficiency, advance dexterity, and enable vital agreements. Digitalization not only maximizing the life of platforms it also reduces the effect of ageing. The predictive maintenance cut down the cost of corrective action and failure. It enhances the life of equipment and machinery.

Innovating methods of drilling revolutionize the operational processes and enhances the life of existing facilities.

2.9.1.4 ENVIRONMENTAL SUSTAINABILITY

The world is moving towards sustainable energy approach and encouraging the venture of renewable energy with subsidies and carbon emission credits. This dynamic and competent atmosphere compel O&G industry to explore advance opportunities to reduce greenhouse gases. In North Sea the O&G exploration process started 40 years ago, so instead of new exploration, environmentally sustainable investment in existing platforms and fields are highly encouraged in term of taxation and other laws. Norway is one of the leading countries in the world, which introduced taxation procedure in Petroleum sector. Norway greenhouse Gas emission trading act were regulated in 2005 and it became the member of EU climate agreement in 2009. The state Oil Company Equinor is reducing carbon emission by storing $C0_2$ deep into North Sea. The carbon capture and storage (CCUS) technology has been widely used across 18 different parts of the world (InternationalEnergyAgency, 2020a). The seabed of North Sea is ideal for storing CO_2. Equinor is exploiting this opportunity of dumping CO_2, which is equal to annual emission of 10 million cars. In northwest of Bergen emission has been pumped through the pipeline into rock formation of 3 km beneath the sea for secure storage (InternationalEnergyAgency, 2020a). The LE is becoming environmentally sustainable method of closed loop economy. In synchronization of Green society, it is highly motivated and encouraged to exploit more opportunities for sustainable energy in existing platforms. Norway are using the best available technology (BAT) and is drastically reducing the emission of NMVOC (non-methane volatile organic compound) in existing and modified platforms (NorwegianPetroleum, 2020b). The Figure 32 shows the history and projection of NMVOC.

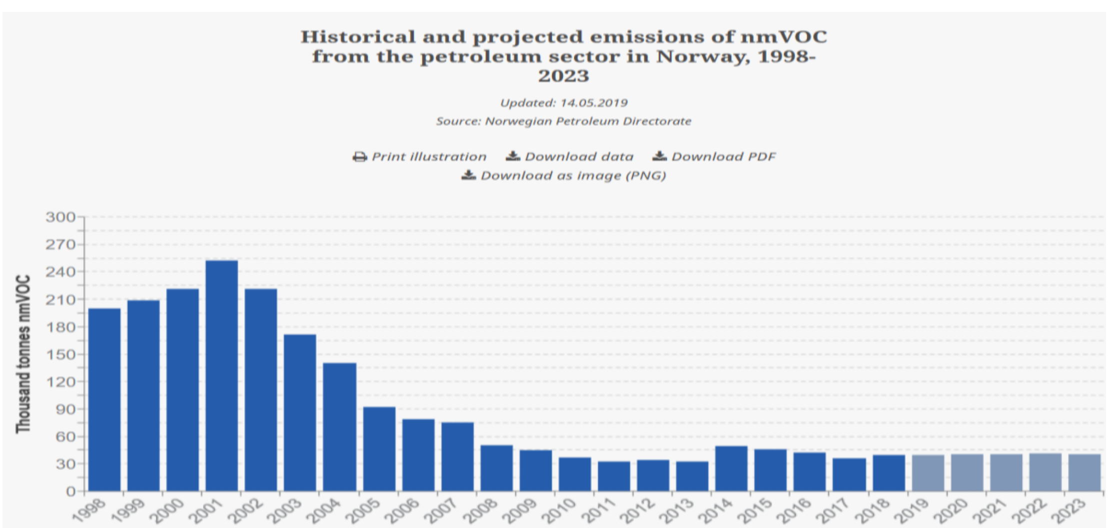


Figure 32: Projected Emission of NMVOC (NorwegianPetroleum, 2020b)

2.9.1.5 SAFETY INTEGRITY

As the equipment get old and time passes, the safety integrity of the system declines and reaches to minimum level at the end of design life of substance. The process of LE is to demonstrate and documents that the facility or system is fit and safe for use. During the enhancement procedure of design life, the safety threshold limits of equipment's must be enhanced by maintaining the safety integrity of the system (Wintle & Sharp, 2008). Expanding the safety limits of the system is the pre-requisite to LE phenomenon and one of the main boundaries and constraints under LE process can occur. The LE process also should indicate the main barriers and their safety limits according to design life and their predicated integrity and performance.

Complex system and equipment progressively utilizing the electrical, electronic, or programmable electronic system to execute various operation and few of have severe and significant safety implications, if system breakdown or fail to perform accurately (AMOG, 2020). The LE of such component or system is highly sophisticated job by maintaining the safety integrity of equipment and enhancing the design life of system.

3 SYSTEMATIC DEVELOPMENT OF LE FRAMEWORK FOR MAINTENANCE AND OPERATIONS

The framework for LE has been developed in consideration and compliance to standards and general guidelines for LE process. In section 3.1 the relevant standards and guidelines are described which will be used during the development of framework.

3.1 RELEVANT STANDARD AND GUIDELINES

Technical advancement of suggested framework has been processed, keeping in view all the standards and codes for collection of reliability and maintenance data, production assurance and reliability management. Also following the general guidelines for Risk based maintenance and inspection.

Following below is the illustration of general guidelines for LE in NCS and the main standards that needs to follow during the assessment and execution procedure of LE (StandardsNorway, 2020).

3.1.1 NORWEGIAN OIL INDUSTRY ASSOCIATION (OLF) GUIDELINES-122

In NCS, there is Norwegian Oil and Gas recommended guidelines for the management of life extension i.e. Guideline 122. Norsk Olje & Gas has issued these guidelines for how the operators can assess and documents safe operation beyond the design life (NorskOlje&gas, 2020a). All the companies operating in the region must strictly follow these guidelines and develop their own standards and codes during advancement procedure of LE.

The facility installed on the NCS are always designed to be used for a period as given by their manufacture, fabricator, and supplier. The period is the design life of the system and equipment. It varies inside of the facility or platform, different component inside of the system has varies design life period. The economic life of a facility may change, requiring a life for the facility that exceeds the design life. When this occur, there shall be a process to extend the life of the system. The life extension process should determine that safe, reliable, and integrated operation for the extended period is attainable.

3.1.1.1 LICENSE MANAGEMENT

The companies awarded a production license enter into an agreement for petroleum activities, the license agreement. The Joint operating agreement (JOA) is an attachment to the license agreement and explains how the production license is governed (NorskOlje&gas, 2020a).

The most relevant JOA sections related to life extension are (NorskOlje&gas, 2020a):

1) Requirement for corporate governance

2) Long-term plans
3) Risk management

The license management committee should approve the extended life and ensure that the extended life is in line with the objectives for the system or platform.

3.1.1.2 RISK MANAGEMENT

The license management committee also ensure the operator and user that it has a process to handle the risk links with platforms and all the risk mitigation measures have been implemented. All the risk that identified during the process of LE, should be included in the license risk management process (NorskOlje&gas, 2020a).

3.1.1.3 PLANS DEVELOPMENT AND ASSESSMENT OF TECHNICAL LIFETIME OF A SYSTEM

The operator develops plan for activities that insure the safe operability of system. There is inclusion of following activities in the plan development (NorskOlje&gas, 2020a):

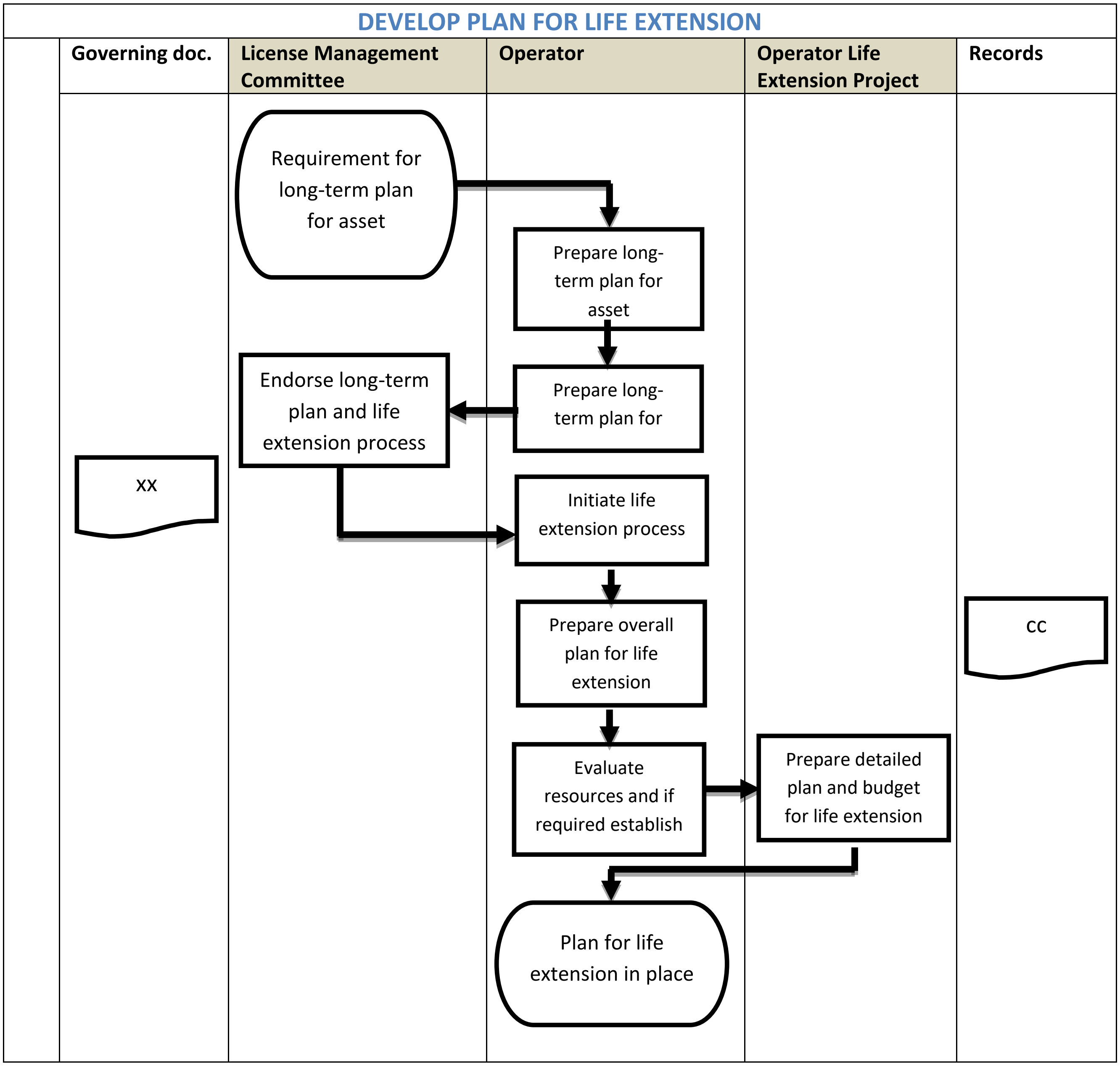
1) Modification adopts by the system according to future needs
2) The equipment and system replacement
3) Strategic selection procedure and requirement for maintenance

The technical lifetime of a system can be determined by predicting when the condition reaches the acceptance level. The assessment of technical lifetime of equipment is assessed on the following parameters (NorskOlje&gas, 2020a):

1) Degradation from operational use
2) Prediction models
3) Maintenance experiences and history evaluation
4) Inspection outcomes
5) Obsolescence

After extensive workout and experiences it is indicated that the LE should be started at least 2 years before the design life exceeded (NorskOlje&gas, 2020a). The Table 5 represent the detail develop plan for LE, according to Norwegian O&G recommended guidelines 122.

Table 5: Plan for LE (NorskOlje&gas, 2020a)



3.1.1.4 UNCERTAINTY IN LE MANAGEMENT

The prediction of the lifetime of a solo system or equipment on a platform is a bit challenging task and there is a lot of uncertainties associated to that prediction process. So, there is a need to recognize and quantify these uncertainties during the process of LE (NorskOlje&gas, 2020a). The operator should endorse the adoption of advance technologies in LE phenomenon and should understand and realize that further information cannot be gettable with existing resources and technologies (NorskOlje&gas, 2020a). The LE process should identify the information that is required to mitigate the uncertainty during the assessment procedure, and this is one of the vital step or factors in the risk management of the LE.

This is the responsibility of operator to identify and recognize the systems that should be assessed in the LE process. It normally includes the equipment that is required safe and reliable operation where degradation and obsolescence already occurred or identify as a potential deteriorator event. The operator should illustrate and define all the standards that are required during assessing and executing process of LE (NorskOlje&gas, 2020a).

3.1.1.5 ASSESSMENT OF SYSTEM CONDITION, FUNCTIONALITY, AND TECHNICAL LIFETIME

During the assessment process of LE, the user must check the current condition of the system. Following are the main activities that needs to be considered during detail assessment procedure of LE (NorskOlje&gas, 2020a).

1) Review operational history, maintenance, and inspection records
2) Assessment of the need for further inspection
3) Consultation with original equipment manufacturer
4) Review of the operational limits
5) Assessment of LE for wells carried out with reference code NORSOK D-010.
6) LE on drilling is carried on accordance with NORSOK D-001

In consideration of technical of perspective, following are the below main parameters that needs to consider during the assessment process of LE (NorskOlje&gas, 2020a)

1) Review of maintenances strategies
2) Quantitative analysis in case of predicable degradation mechanism
3) Assess the need for further modification or upgradation of system.
4) Assess to change the operational limits of the system
5) Highlight key assumptions that influence the uncertainty related to the LE

3.1.1.6 LE PROGRAMMED AND CRITERIA

The LE process may identify the considerable modification that requires a review and update of Total Risk Assessment(TRA).It’s the responsibility pf operator that he should recognize these changes to procedures and implements these at the appropriate time. The operator also should develop a budget and comprehensive programmed that contains all the measures identified during the process of LE (NorskOlje&gas, 2020a). And based on this program the user develops a business case for LE to the license management committee.

The extended life of the systems and facility should be based on the following criteria as per Guideline 122 (NorskOlje&gas, 2020a).

1) Compliance with applicable regulations
2) Compliance with Operators own requirements for safe and reliable operations.
3) Acceptable control of Condition throughout the extended life.
4) Acceptable management of the barriers throughout the extended life
5) Acceptable safety level throughout the extended life
6) Maintaining acceptable risk levels throughout the extended life.
7) Acceptable monitoring and control of degradation through maintenance management
8) Acceptable management of change throughout the extended life.
9) Operational limits as specified for the facility.

The operator shall ensure that the assumptions that are being made for extended life are verified and approved and documented before the design life exceeded. This is the responsibility of user for ensuring that system is not being used beyond their extended life (NorskOlje&gas, 2020a).

3.1.1.7 APPLICABLE STANDARDS FOR LIFE EXTENSION

In Table 6 there are the main standards and methodologies that are relevant and applicable during the process of LE in NCS.

Table 6: Applicable Standards (NorskOlje&gas, 2020a)

S/NO	DESCRIPTION	STANDARDS
01	Drilling system	NORSOK D-001 and NORSOK D-010
02	Production assurance and reliability management	ISO 20815:2008
03	Collection of reliability and maintenance (RM) data	ISO 14224:2016
04	Riser and pipeline transportation systems	NORSOK Y-002
05	Risk based maintenance and inspection	NORSOK Z-2008
06	Obsolescence of systems	IEC 62402:2007
07	Offshore cranes	ISO 12482:2014. NORSOK R-002:2012
08	Offshore Load bearing structure	NORSOK N-009
09	Wells	NORSOK D-010

The Table 6 describes the main standards that are applicable and relevant in the LE process. In consideration of the scope of work, these three standards (ISO 20815:2008, ISO 14224:2016, NORSOK Z-2008) will be used in development of framework, described in section 3.2.

3.1.2 PRODUCTION ASSURANCE AND RELIABILITY MANAGEMENT (ISO 20815:2008)

The scope of work that is included in this international standard is the production assurance within the systems and operations connected to exploration drilling, processing and transportation of petroleum and natural gas products (ISO, 2020). This standard provides guidelines for systematic management, efficient planning, execution and use of production assurance and reliability technology. The main purpose of this standard is to gain the cost-effective solution considering the whole life cycle of the project. Following below are the main elements that are required to accomplish the profitable solution over the life cycle of the asset development project (ISO, 2020).

1) Production assurance management for optimum economy of the system through all its life phases
2) Planning, commissioning, and implementation of reliability technology
3) Operational application of reliability and maintenance statistics
4) Reliability design and improvement in operational modes of the system.

3.1.3 Reliability and Maintenance Data (ISO 14224:2016)

This international standard provides a complete and comprehensive foundation for gathering the reliability and maintenance (RM) data in a standard format for equipment in all facilities and operations within petroleum and natural gas industries (InternationalStandardsISO14224, 2016). This standard establishes requirements that any in-house or commercially available RM data system be required to meet when design for RM data exchange.

Following below are the main areas in which data to be collected (InternationalStandardsISO14224, 2016):

1) Equipment data, e.g. equipment taxonomy, equipment attributes
2) Failure data e.g. failure cause, failure consequences, failure mechanism
3) Maintenance data e.g., maintenance action, resource used, maintenance consequences, down time.

Following below are the main areas in which this data can be used

1) Availability e.g. equipment availability, system availability and plant production availability

2) Maintenance e.g. corrective and preventive maintenance, maintenance plan and supportability
3) Safety and environment e.g. equipment failure with adverse consequences for safety.

This international standard does not apply to following (InternationalStandardsISO14224, 2016):

1) Data on direct cost issues
2) Data from laboratory testing and manufacturing
3) Complete equipment data sheets
4) Additional on-service data that on operator, on an individual basis, can consider useful for operation and maintenance.
5) Methods for analyzing and applying for RM data.

3.1.4 RISK BASED MAINTENANCE AND INSPECTION (NORSOK Z-2008)

This NORSOK standards is prepared and published by the support of Norwegian Oil industry Association (OLF), The Federation of Norwegian Industry and Petroleum Safety Authority Norway (PSA). The NORSOK standard provides guidelines in following sections (NORSOKSTANDARDSZ-008, 2011):

1) Establishment of Technical hierarchy of equipment
2) Consequences classification of equipment
3) Use of consequences classification in maintenance management
4) Use of Risk analysis to update PM programs
5) Spare part evaluation

This standard applicable in following phases of equipment and system (NORSOKSTANDARDSZ-008, 2011)

1) Design phase
2) Preparation for operation
3) Operation phase

All type of failure modes and failure mechanism are covered by this NORSOK standard. These standards can be applicable on all type of equipment's in O&G industry except load bearing structure, floating structure and risers (NORSOKSTANDARDSZ-008, 2011).

3.2 DEVELOPMENT AND EXPLANATION OF THE FRAMEWORK

The suggested framework consists of four phases that involves the detail assessment and history evolution of the system, technical assessment and quantify the uncertainty in the system. The last phase is the financial and technical validation of framework. The suggested framework has been applicable to all type of offshore systems and equipment's. The framework proposes the maintenance benchmarking in the consideration of end life management scenario. It also validates the commercial section of maintenance needs and operational requirements, shown in

Figure 33.

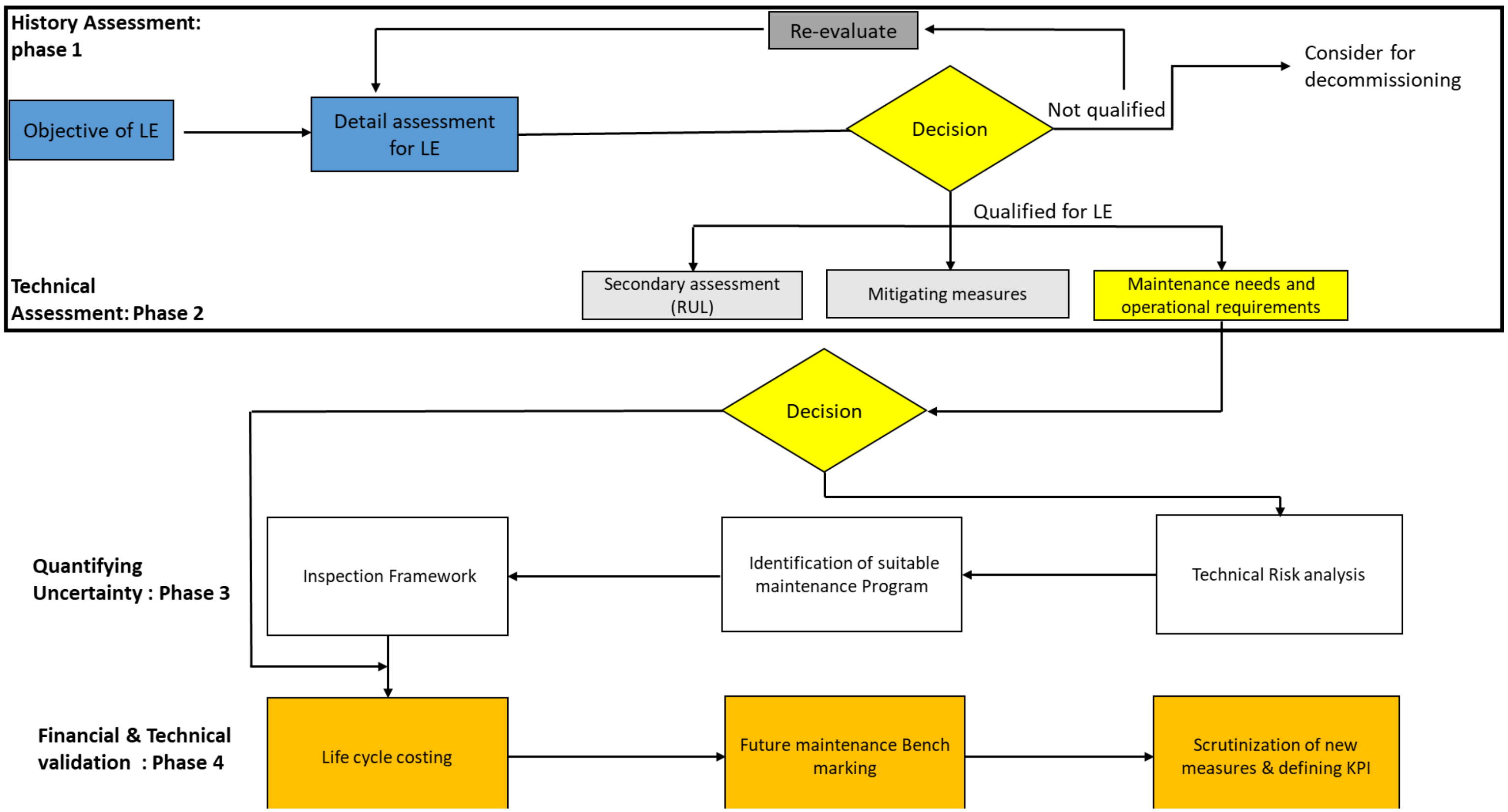


Figure 33: Suggested Framework

The first step in framework is to define and clarify the objective, later the detail assessment of the system will be done that involves the history evaluation of the system. The outcomes of the detail assessment and history evaluation can directly go to phase 2 of the framework i.e. Mitigation measure or action. In phase 1 of the framework **decision** will be made either the system required decommissioning, or it will go for LE process. The results of phase 1 are key and determent factor for next phase initiation.

The Phase 2 sub-divides into three parallel activities and the focus are on maintenance needs of the system and proposing the future benchmarking for the system. If it finalizes that there is no mitigation action required and secondary assessment is also discarded, then essentially maintenance needs and operational requirement of the system will be explored. The identification of failure modes, failure mechanisms and failure consequences are defined in consideration of OLF-122. After collection of reliability and maintenance data and outcomes of detail failure analysis techniques, **conditional decision mode** diverts the system into phase 3 or either to phase 4. If further analysis of the system required or there is need to prioritize the component according to risk profile of the equipment then it moves to phase 3 of the framework. While if there is no further requirement of risk analysis in the system then it can bypass the phase 3 of the framework or move to phase 4 for financial validation and maintenance benchmarking.

In phase 3 detail risk analysis were done on the subsystem or component of the main system. There was a need to scrutinize and prioritize the component in the system according to their vulnerability, risk exposure and maintainability. Later detail inspection framework program was developed in according to the accessibility and material properties of the component. The final stage was to validate the whole phenomenon and process by the comparative analysis and financial prospective. The comparative analysis usually done by comparing the existing maintenance data and technique of the system with adoption of advance technology and proposals. The commercial viability is the key factor in making the circular economy. There should be a definite predictive benchmarking and a time frame for the maintenance intervals.

3.3 PHASE 1: HISTORY AND DETAIL ASSESSMENT

In LE process, the first step is to define the objective of LE and their scope of work. In suggested framework Figure 34**Error! Reference source not found.** the objective of LE is to enhance the life of equipment and safety limits of system.

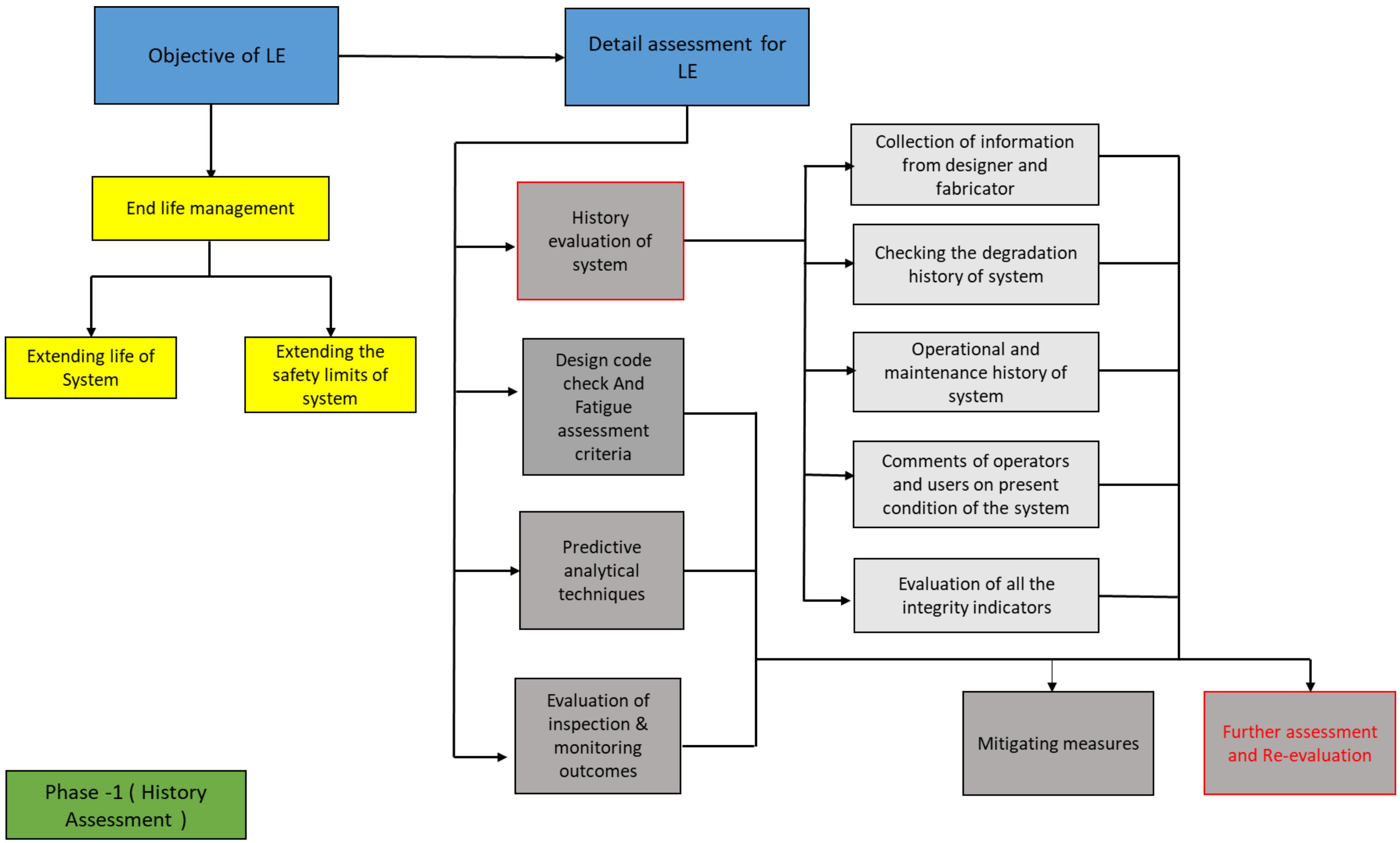


Figure 34: Framework- Phase-1

3.3.1 HISTORY EVALUATION

This phase includes the degradation history of system and the component linked to it. It covers the detail analysis of past work profile and detail assessment of system according to updated drawings, computer models and incorporation of advance technologies. Following below are the main parameters that are required to check during evaluation process of past profile and operational activities of the system.

1. Detail analysis and collection of information from fabricators, designers, maintenance and quality department and operators.
2. The observation and remarks of operators on current condition of equipment.
3. Detail scrutinization of degradation history of equipment and the mechanism that contributed during the degradation process of system
4. The gathering of relevant data and statistics that includes the operational parameters, commissioning documents, original designs and amendments, changes in organization structure, risk and hazard assessment and condition monitoring data
5. During history evaluation process it is vital to collect all the maintenance history of the equipment, relative maintenance programs that being used during their past work profile, and all the inspection data and the techniques being used during the process of monitoring and inspection.

3.3.2 DESIGN CODE CHECK

To figure out and understand the behavior of old existing system, it is very important to recognize the standards and parameters on which fabrication have been done, what are the codes which relates and being used during the operational and maintenance activities of the system. What are the standards of calculations, commissioning, erection, and execution?

During the process of LE assessment, its vital to check all the original design standards and codes and their advance adoption during the operational process of system. This is essential step in evaluation process of framework, it provides basis for future prediction and proposal.

Apart from ISO standards and code formulation, every country and region have their own criteria of design codes. Norway has detail NORSOK standards for their offshore facilities and systems. So, during the detail assessment process comprehensive “Design code check” are considered as a key factor for evaluation of the system.

3.3.3 FATIGUE ASSESSMENT CRITERIA

Fatigue is defined by cumulative material damage caused by extensive cyclic loading during the operational lifetime of system and equipment. It is resulting in damaging the internal framework of system with crack propagation, leakage in welding joints and crack appear through thickness of system. As fatigue cracking is a time dependent event and accumulative degradation mechanism, it badly affects the operating system and design life (Gerhard, Alexander, & John, 2019). With the perspective of end life management, detail analysis and assessment of the effect of fatigue is required. Also, there is a need to determine the fatigue life prediction by using analytical technique and methods.

There are several methods of fatigue analysis but following below are two major analysis method that are used during the fatigue assessment procedure (Gerhard et al., 2019).

1) S-N fatigue analysis
2) Fracture mechanic approach

Both analyses are mostly used in offshore structure assessment under severe cyclic loading and stress condition. The S-N approach is the conventional method of fatigue life assessment and it mostly use the S-N curves in conjunction with a long-term fatigue stress range distribution (Gerhard et al., 2019). The fracture mechanic approach again sublet into fatigue crack growth analysis, fracture assessment and residual stress distribution analysis.

3.3.4 PREDICTIVE ANALYTICAL TECHNIQUE

The O&G industry investigate various analytical and advance method to shrink the performance gap of 200 billion dollar. The conventional SCADA system, simulation tools, extensive study and data management cannot bridge the gap of financial performance. In advance world of O&G production, the predictive analytical techniques are being used to enhance the financial performance, maintain the operational and maintenance data, smoothing the commissioning process and enhancing the drilling performance of the facility. During the process of LE, it is viable to consider the results of predictive analytical techniques and use these results in assessment procedure of LE. Following below are the five main requisites to exploiting the advance and modern analytical techniques (Mckinsey&Company, 2020).

1) Data availability
2) Analytical infrastructure
3) Analytical skills and capabilities
4) Business driven agility
5) Redesign work and management

During the process of LE assessment, users gets the information from the relevant sections and these data helps in predictive benchmarking of the system and equipment.

3.3.5 INTEGRITY INDICATORS

After detail assessment and history evaluation in phase 1, if further re-assessment is required then there is a need to re-consider the integrity indicators. The integrity indicators of the system can be re-evaluated and re-examine in synchronization of equipment threshold limits. The compliance to all integrity indicators also requires during the validation process of LE and advance methodology adopted by the system. The conformity and compliance to integrity indicators are a step forward to reliable system operations.

In LE process the information regarding the system should be clear and smooth. To ease and expedite the phenomenon of LE, the Figure 35 explains the key integrity indicators with detail examples.

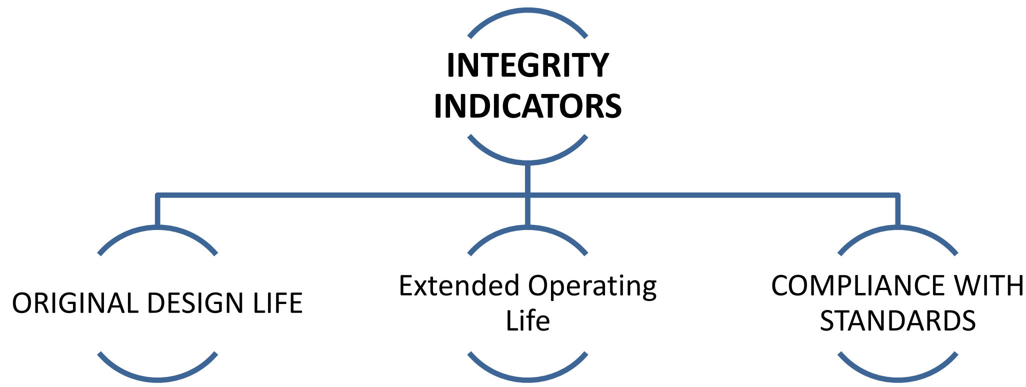


Figure 35: Integrity Indicators

3.3.5.1 ORIGINAL DESIGN LIFE

During the process of offshore installation, the design life period is subject to put forward in according to their persistency and reinforcement in the structure and platform. The nominal design life for some equipment is mostly specified because of the lack of exposure to inspection and analysis (Wintle & Sharp, 2008). All other equipment's and platforms are installed without a definite and precise design life period. These installations are subject to continuation of periodic inspection, monitoring and assessment (Aeran & Siriwardane, 2019)

The expected life of equipment and platform depends upon the prevailing engineering familiarity and proficiency. In some operation or areas, the design life also set to put certain margin, erosion allowance and fatigue. Moreover, it validated the level of quality to purchaser, fabricator, and manufacturer (Wintle & Sharp, 2008). The authentication of this affirmation should be actual realized and recognized by actual experiences.

As an indicator of integrity, the design life is still an appropriate dimension either it contains a lot of rough and crude element in their assessment. The expected life assurances show the experiences of designer and manufacturer. As equipment becomes older the operation of integrity management becomes less effective, to undo this phenomenon a broader term view of integrity and basis for assurance is required (Wintle & Sharp, 2008). The designers and fabricators put forward the design life period as a basis for life extension review.

3.3.5.2 EXTENDED OPERATING LIFE

This is not potential integrity indicator but to assess and determine the future integrity an estimation of extended operating life required. The anticipated extended operating life empower and implement the new benchmark assessment that integrity will be retain and sustain while the integrity management measures should insure this process (Wintle & Sharp, 2008). The AEOL should be specified with period and date in all items either they are unaffected by the level of production or activities because in some cases operating life may be finished before that anticipated. To extend the life beyond the anticipated a further workout and submission is required (Wintle & Sharp, 2008). In short operating life provides an advantageous and convenient tool to maintain or envision the safety threshold limits.

3.3.5.3 COMPLIANCE WITH STANDARDS

To justify the purpose of LE, the possible symbol of integrity are assessment and compliance of standards in structure, system, component, and installation formulation. In Figure 36 there are the issues that needs to be addressed in consideration of compliance requirement (Wintle & Sharp, 2008).

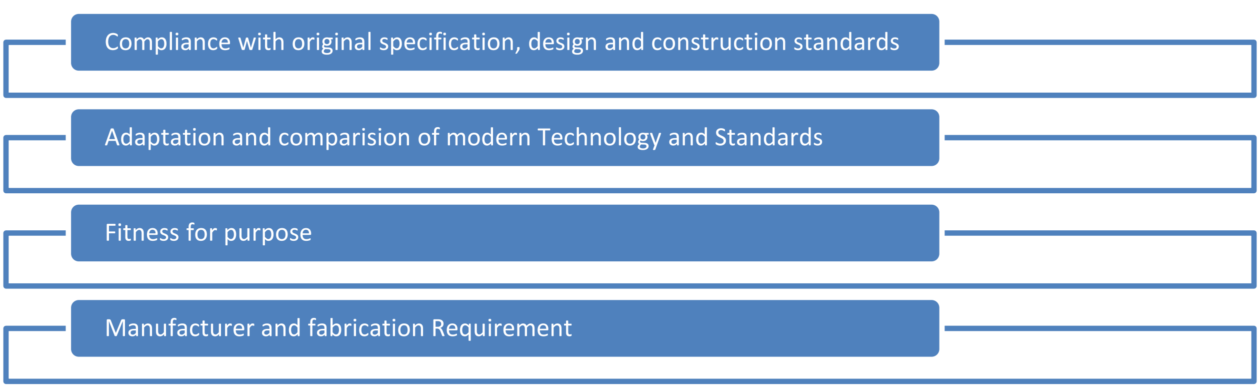


Figure 36: Issues of Integrity

3.3.5.4 COMPLIANCE WITH ORIGINAL DESIGN

During the process of LE, it is highly suggested to confirm if either the equipment or the facility on offshore platform meet the original standards of design, fabrication, manufacturing, and construction. It needs to be evaluated if equipment is operating under the prescribed safety limit defined by designer or it is crossing threshold value (Wintle & Sharp, 2008).

In NCS, NORSOK standards developed by Norwegian Petroleum authority to ensure the acceptable safety limits, value adding and cost effectiveness for offshore/onshore O&G facilities and production installation. NORSOK standards are developed to replace the O&G companies' specifications and it made a reference point in jurisdiction/regulation (StandardsNorway, 2019). There are more than forty years of experience of Norwegian petroleum industry behind the NORSOK standards. The abbreviation NORSOK originally stands for "Norwegian shelf competent position" and was popularized in 1994 to cut the expenditure and adding more value in proficient and qualified working environment (StandardsNorway, 2019). The Figure 37 shows us all the standards that must be used by Norwegian Petroleum industry in NCS.

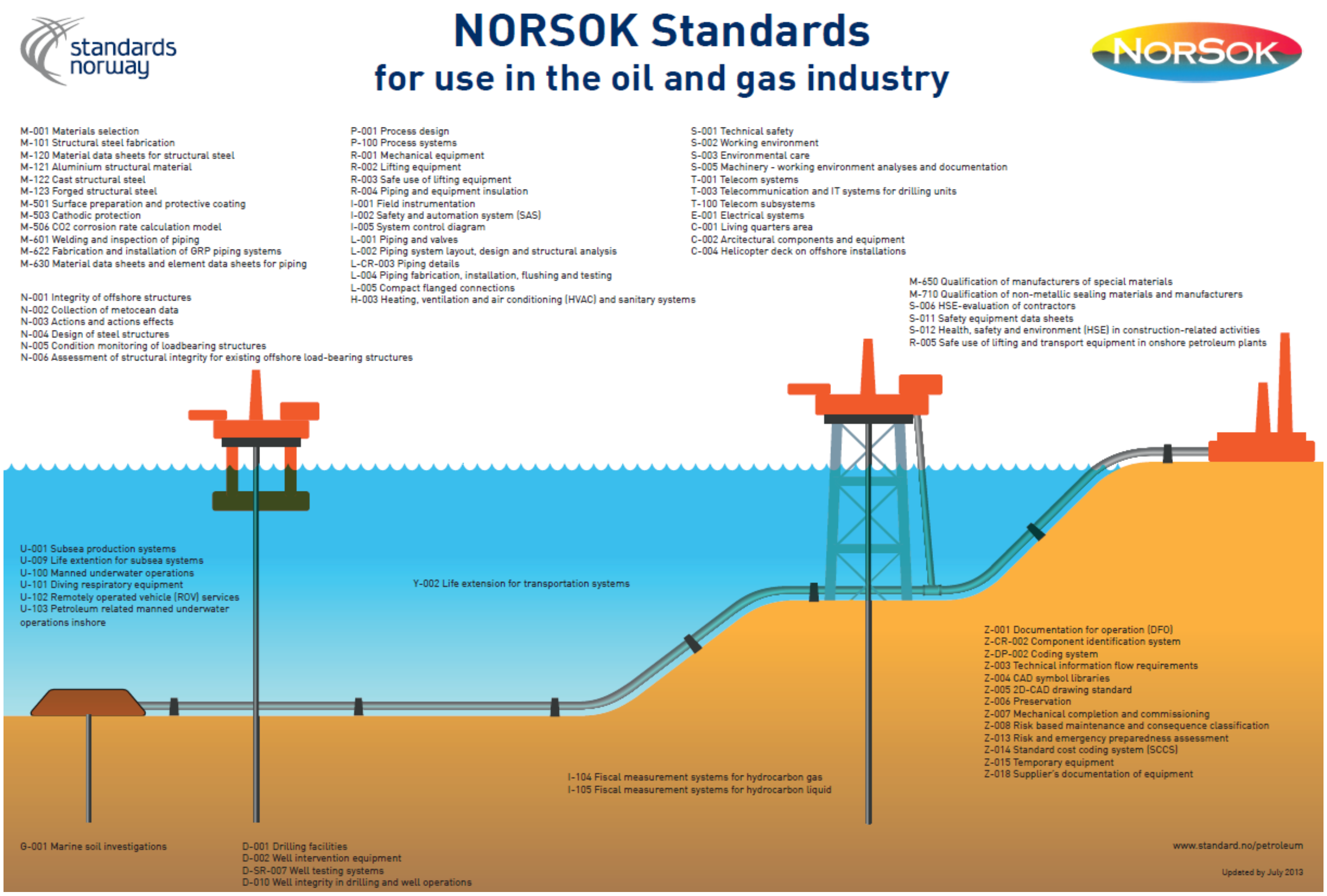


Figure 37: NORSOK Standards for Oil and Gas (StandardsNorway, 2019)

3.3.5.5 COMPARISON WITH MODERN STANDARDS

One of the vital steps for LE process is to identify the new challenges and advancement in term of standards and specifications. It also needs to consider these changes in engineering standards and safety limits and to build such compatibility among facilities and operators so that they can pursue their work without harming the safety limits and new codes (Wintle & Sharp, 2008). There should be a comprehensive comparison between original standards and new advanced codes. Sometimes there is a need to replace the old codes to new one. In case of equipment installation and production facilities, thorough assessment should be made to check either the existing material is compatible to new norms or we need to change and replace the material (Wintle & Sharp, 2008).

The rigid and stern compliance to advanced standards is purely dependent about O&G field and risk associated to it. The inspection team generally thoroughly monitor the situation and present the risk profile of the equipment to the authorities and production operators (Wintle & Sharp, 2008). The comprehensive comparison with current standards can only analyze that where the offset of mature design need reinforcement or where compensatory steps are required or where you may need additional integrity management mechanism to absorb the shock of modernization and advancement (Wintle & Sharp, 2008)

One of the prime examples in O&G industry is pressure equipment and various welded fabrication installations that are designed and adhere to old standards and codes while their existing design may not have estimate for fatigue failure. The modern norms make sure and include complete fatigue failure standards.

3.3.5.6 FUNCTIONALITY REQUIREMENTS AND FITNESS-FOR-PURPOSE

The assessment of functionality of equipment and fitness-for-purpose in present service and application is one of the indicators of integrity. There is a need to check if the installation and production facilities meet the original design criteria and compatibility with adaptation of modern technology (Wintle & Sharp, 2008). During operational activities sometimes the equipment may not be overloaded during the whole life cycle and some facilities expose to harsh weather conditions and environmental parameters. The equipment's that are downrated to fewer demanding activities are mostly functionally fit for purpose even without performing major maintenance inspection and assessment (Wintle & Sharp, 2008). While the equipment's and facilities that are exposed to high demanding activities needs thorough evaluation and monitoring during the operations because these equipment's downgraded, and their life ended before the planned one.

In some of equipment's and installations the lack of functionality is visible with naked eye and normal maintenance activities (Wintle & Sharp, 2008). In case of handrail and walkways the corrosion is easily visible to inspector or operators of the platforms. Also, the breakdown of the active system, leakage from joint seals and welding cracks are unclear and explicit. While in some cases deeper knowledge required for example in flow rate performance of pumps, compression pressure of compressors, internal erosion and corrosion of pipes, material degradation inside of the pipe and vessels, l (Wintle & Sharp, 2008). To overcome all these concerns detail functional evaluation is required with schedule testing, analysis, monitoring, inspection, and assessment.

3.3.5.7 FABRICATION REQUIREMENTS

The construction and manufacturing standards of fabrication are a vital examination regarding the process of LE. The impoverished and indigent fabricated materials and installations are more prone to ageing mechanism (Wintle & Sharp, 2008). Sometimes the most defenseless and susceptible system requires replacement and reinforcement, it is evident that whenever the life of facilities is predicted, it should consider the material standards, fabrication norms and practices in their forecasting (Wintle & Sharp, 2008). The Figure 38 explains the prognostic of poor fabrication standards that are often considerable during inspections procedures.

Figure 38: Poor Fabrication Standards

The Table 7 describes and illustrates all the relevant international standards that are being used during the development of the phase 1 of the framework. The relevant clauses along description has been mentioned below.

Table 7: International Standards

S/NO	ISO 14224:2016	ISO 20815:2008
01	Obtaining quality of data (Clause 7.1)	Design life (Clause 3.1.6)
02	Planning measures (Clause 7.1.3)	Fault tolerance (3.1.15)
03	Data sources (Clause 7.2.2)	Operating state (3.1.30)
04	Data collection periods (Clause 8.3.2)	Performance requirement (3.1.33)
05	Maintenance Data (Clause 9.6)	Design and manufacturing for production assurance (Clause B.3)
06	Obtaining quality of data (Clause 7.1)	Production performance data (clause E.3)

07	Surveillance and operating period (Clause 8.3.1)	Performance and operability review (clause I.8)
08	Mid-stream (clause 3.65)	
09	Predictive maintenance (Clause 3.77)	
10	Reliability data (clause 3.82)	
11	Upstream (Clause 3.98)	
12	Maintenance record (clause 3.55)	

3.4 PHASE-2: TECHNICAL ASSESSMENT

Once the system and equipment are qualified for LE, the technical evaluation and assessment started with relevant applicable techniques. In literature review, the systematics detail about remaining useful life (RUL) is already been explained. This section will illustrate detail about mitigation measures and what are the maintenance needs and operational requirements of the system, shown in Figure 39.

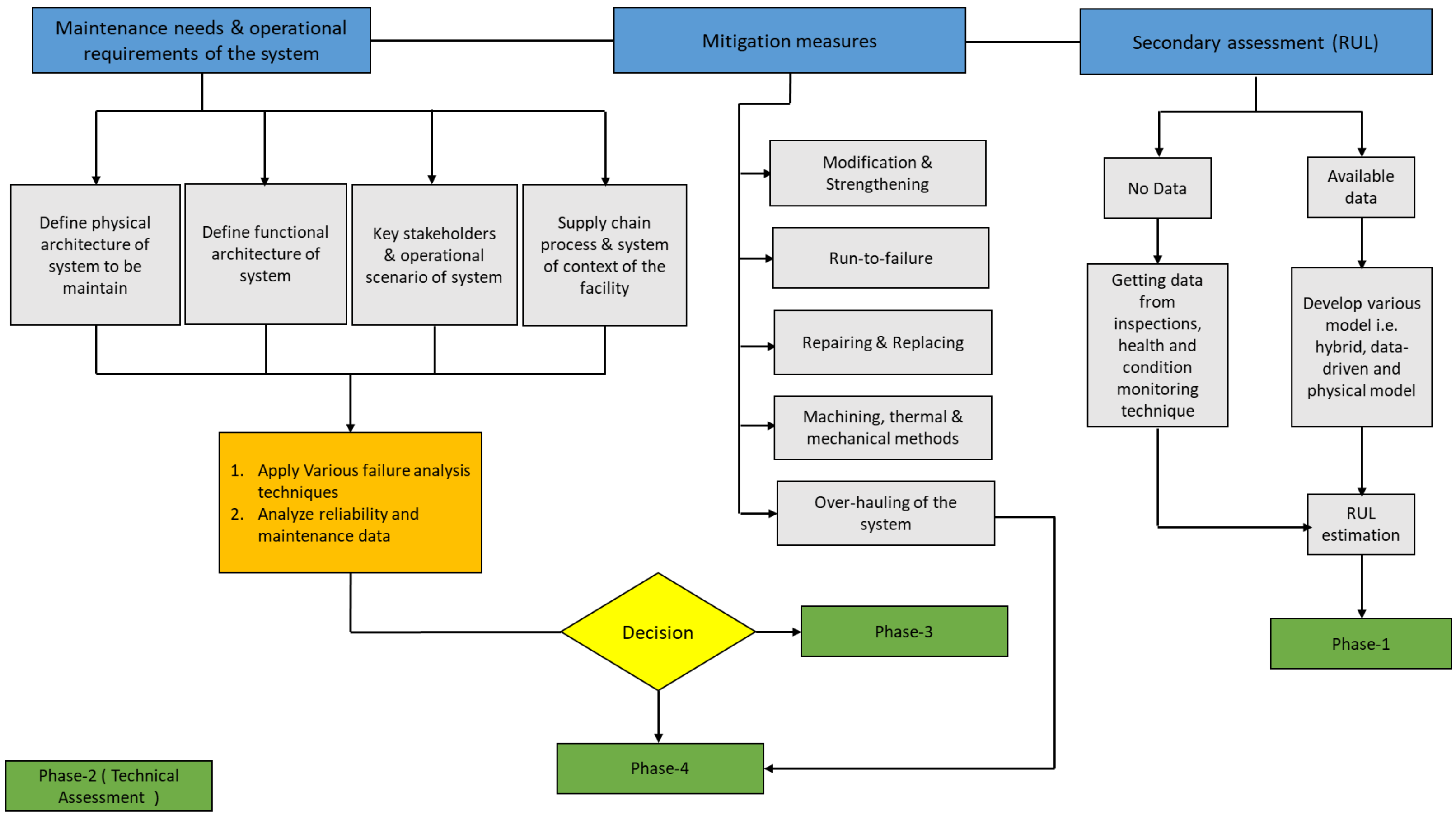


Figure 39: Framework-Phase-2

3.4.1 MITIGATION MEASURES

In offshore O&G industry, mitigation and remedial measures may be required when damage found in the system during inspection process. The mitigation process is associated with the reduction of potential failure for the system that are degraded or deteriorated and can be repaired, strengthen, modified, and replaced with advance elements matching compatibility. If during the process of LE assessment, the inspection results are alarming, then operators are supposed to take mitigating steps directly. Following are the main mitigating measure that mostly takes place in O&G industry.

3.4.1.1 STRENGTHENING

It involves the strengthening of steel jacket structure, improvement in welding methods and techniques, bolstering the system by extra support and clam technology i.e. mechanical clamp and neoprene-lined clamp. The welding improvements method further categories into advance techniques such as TIG dressing, plasma dressing, laser dressing and water jet gouging (Gerhard et al., 2019).

3.4.1.2 REPAIRING

In mitigation measures, the repairing of the system or equipment are considered as vital tread. Keeping in view the economic prospect of the repairing, it is highly suggestable to do Level of repair analysis (LORA) and confirm their economic viability. After LORA analysis it is clearly seen that it should either be proceeding with the complete repairing process or discard this step and replace the component or assembly. The repairing process further sublet into three steps

1) Discard Repair
2) Supplier Repair
3) Intermediate Repair

3.4.1.3 MODIFICATION AND MECHANICAL METHODS

There are mechanical methods that are being used to mitigate the effect of system damage or failure. The mechanical peening methods includes hammer peening, needle peening, shot peening and ultrasonic peening. Few thermal techniques involve thermal stress relief, spot heating and Gunnert's method. The mechanical process further sublets in branches such as mechanical overload methods and machine methods. The machining techniques mainly consists of burr grinding and disc grinding (Gerhard et al., 2019). In modification process in O&G industry following is consider, residual stress modification methods and re-melting techniques.

3.4.2 MAINTENANCE NEEDS AND OPERATIONAL REQUIREMENT

To enhance the life of equipment, there is requirement of system to be maintained. If the system is qualified for extensive maintenance program, then there is a need to define or describe all the relevant elements of the maintain system discretely. The first step in maintaining the system is to define their functional architecture. Once these functional architectures recognize then there is requirement to illustrate all the physical architecture aiding and supporting these functional parameters of the system. There is also needed to consider all the physical blocks that works as a catalyst during the functional operation of the system to be maintained (Nyman & Levitt, 2010). The second step is describing the relevant stake holders and then in sequence the supply chain process, system of context of the equipment, operational scenario, and life cycle process of the system.

1) **Describe the functional and physical architecture of the selected system to be maintained.**

This process can be described in detail by IDEF or sequential diagrams, according to the operational and maintenance requirement of the system.

2) **Define needs and requirement of the maintain system, keeping in view the operational scenario of the equipment.**

In Table 8 all the general maintenance needs & operational required described.

Table 8: Maintenance Needs and Operation Requirements

	Stakeholders	Needs	Requirements
Operation and Maintenance (O&M)	User	The client needs a clear and sincere system to trust it for solving their requirements and needs.	The system should be changeable of operations and objectives such as availability, extensibility, trainability etc.
	Management	Management should perform all the financial information of project, stakeholders and shareholders and other financial parts.	The system should collect all information with focus on providing it to the managers.
	Self-maintenance unit	Unit should recognize the software challenges and be able to solve or develop deviation report	The system should be able to detect errors and improve software challenges.
	Financial Operation (Bank)	The bank needs a deep relationship to time-benefits. This means that bank needs to earn benefit in the execution of project.	The money should be transfer immediately by the system, so it decreases the time needed for paying.
	Detection System (Hardware)	Vehicles and station should send and receive their information.	The system should be able to send and receive the data with the use of detectors.
	Software	The data should be transfer between the vehicle and station by the software.	The system using the software should be able to transfer the data.
	Data processing	The data should be transfer between vehicles and station.	During the whole project, the system should make a data processing between vehicles and station.
	Automation system	The informational data should automatically be sent to station.	The system should be able to transfer the important informational data from vehicles quickly to the station.

3) **Illustrating key stake holders, life cycle and supply chain process of the selected system in Figure 40.**

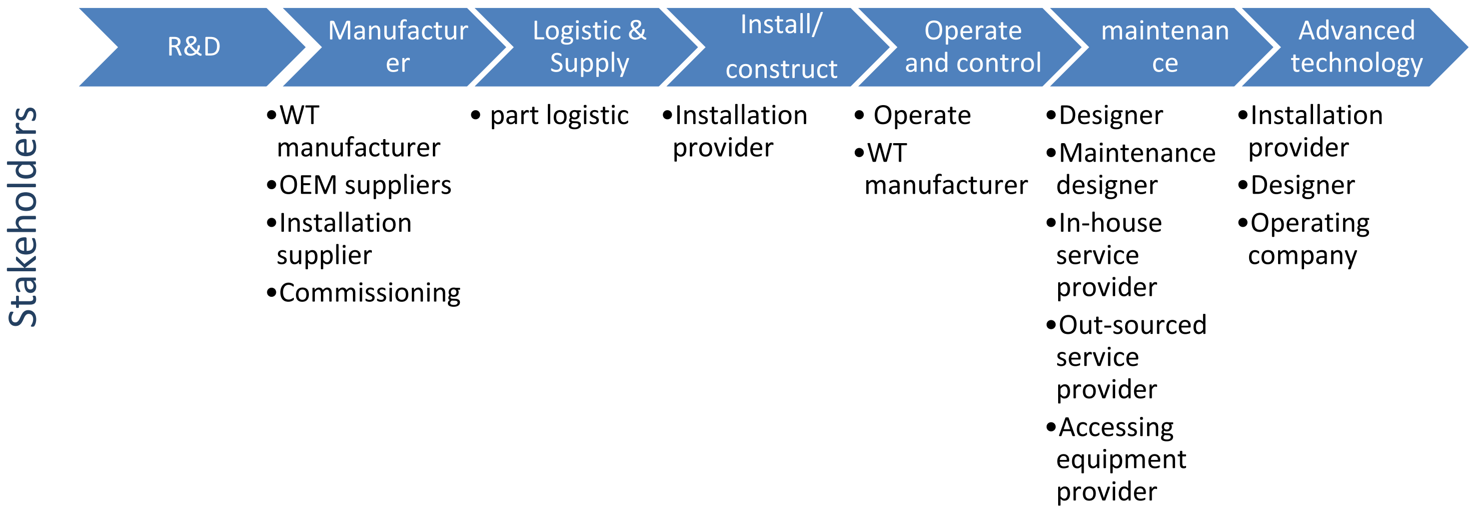
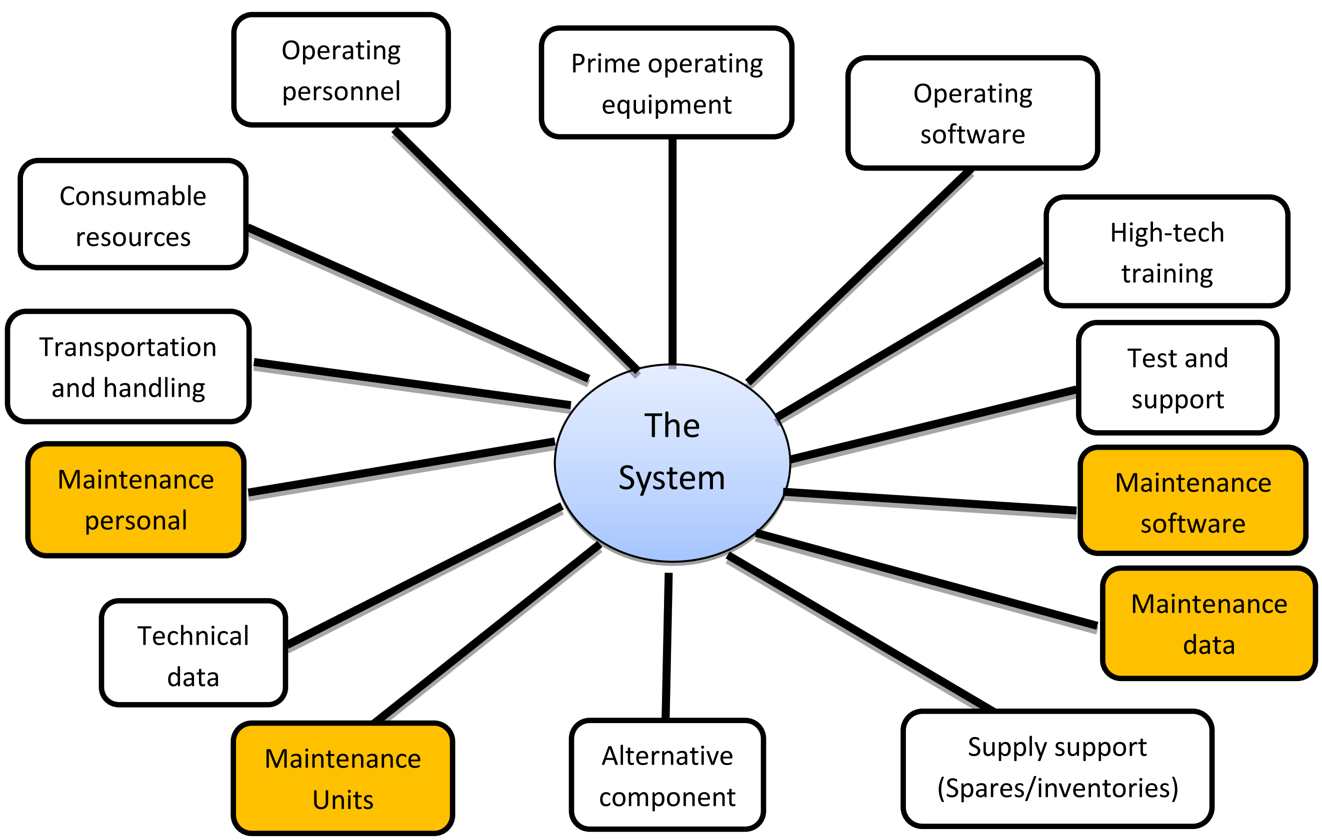


Figure 40: Key Stakeholders

4) **Describe the system context of the equipment/system to be maintained.**



3.4.2.1 *FAILURE ANALYSIS TECHNIQUES*

Every product and system have modes of failure and their analysis helps the designers and operators to recognize the potential risks and uncertain event in the life of system. There are various methodologies been developed to quantify the effect of failure. The failure analysis performs to ensure the quality of equipment, it prevent equipment malfunction, helps in process development, prevent safety or environment hazards, and enhance the system quality and life.

Following below are few major failure analysis techniques that are being used in offshore O&G industry

3.4.2.1.1 FAULT TREE ANALYSIS (FTA)

This is the logic diagram that shows the relation between critical event in the system and the main causes of that event. It is the deductive failure analysis and it may handle multiple failure analysis. Following below are the main elements of FTA shown in Figure 41.

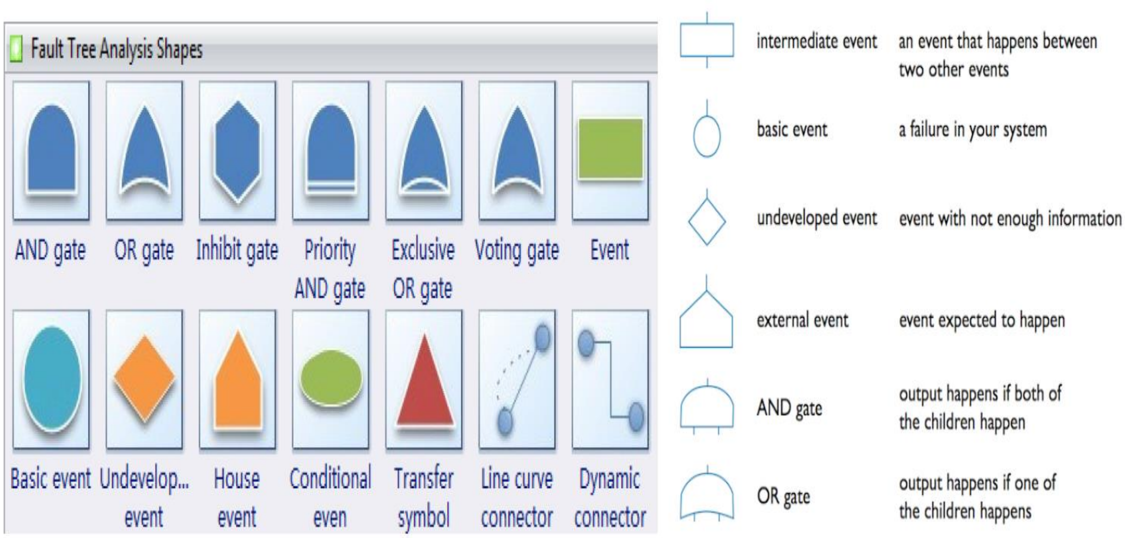


Figure 41: FTA Tools (IdrissEl-thalji, 2019b)

3.4.2.1.2 FAILURE MODE AND EFFECT ANALYSIS (FMEA)

This is the process of analyzing as many elements, components, assemblies, and subsystem to identify the potential failure mode of the system and their effect on the equipment. Following below are the main 10 steps required during the operational mechanism of FMEA (Generalmanagement, 2014).

1) Review the process
2) Brainstorming potential failure mode
3) Listing potential effect of failure
4) Assign severity ranking
5) Assign occurrence ranking
6) Assign detection ranking
7) Calculating RPN
8) Developing action plan
9) Take action

The difference between FMEA and FMECA is addition of critical component and analysis. If we add the Risk priority number (RPN) in FMEA then it becomes FMECA .The FMEA helps the maintenance people to identify the requirement while FMECA helps to find the maintenance requirement in a system where there is lot of man-machine interface (Generalmanagement, 2014).

3.4.2.1.3 RELIABILITY ANALYSIS

It is used to estimate the reliability of each component or whole system by including all the functional and physical architecture of the system. It involves all the steps of root cause analysis, failure mode and effect analysis and high-level failure cause analysis (Smith & Institution of Chemical, 2011). If we have data of number of failures and the total operating hours, we can easily find out the instantaneous failure rate and (Mean time between failure) MTTB through reliability function (IdrissEl-thalji, 2019b).

- Reliability function

$$R(t) = e^{-\lambda * t}$$

Where

λ is the instantanous failure rate.

$$\lambda = \frac{number\ of\ failures}{total\ operating\ hour}$$

$$MTBF = \frac{1}{\lambda}$$

There is also other various analysis that can be used according to operational condition and maintenance requirements of the specific system. There is often used maintainability analysis that includes the estimation of maintainability, functional architecture of the equipment, the LORA analysis, maintenance labor time analysis and maintenance frequency analysis.

3.4.2.2 RELIABILITY AND MAINTENANCE DATA

The second phase of maintenance need and operational requirement is to identify and define all the failure modes, their causes, consequences, failure conditions, critical failure mode and failure conditions etc. (Smith & Institution of Chemical, 2011).

Item name & No	**Failure modes**	**Failure mechanism and causes**	**Mean failure rate**	**Mean time to failure (MTTF)**	**Failure consequences**	**Failure conditions**	**Condition monitoring of Failure modes**	**Regulatory Requirements**	**Critical failure mode**	**Critical failure mode mechanism, MTTF, cause and failure consequence**	**Detail of PM activities and Strategies**	**Equipment shut down time interval & Accessibility to site**
COMPONENT/EQUIPMENT NAME										**Component Critical Failure details**		

The Table 9 describes all the standards with relevant clauses that are being used in the development of phase 2 of the framework.

Table 9: ISO & NORSOK STANDARDS

S/NO	ISO 14224:2016	ISO 20815:2008	NORSOK Z-2008
01	Maintenance plan (clause 3.54)	Maintenance support performance (clause 3.1.23)	Maintenance Program and handling of ageing (clause 8.6)
02	Maintenance concept (clause 3.50)	Mean time between failure, MTTB (clause 3.1.24)	Prioritizing maintenance activities (clause 9.2)
03	Failure mechanism (clause 3.29)	Failure mode and effect analysis (clause I.2)	Key performance indicators for maintenance management (clause 10.3)
04	Failure mode (clause 3.30)	Fault tree analysis (clause I.3)	
05	Failure rate (clause 3.32)	Mean time to repair (3.1.26)	
06	Failure data (clause 9.5)	Reliability (Clause 3.1.41)	
07		Risk and reliability analysis (Clause B.5)	

3.5 PHASE 3: QUANTIFYING UNCERTAINTY

Once the identification of failure modes, mechanism, and failure consequences has been finalized in the system then there is a need to prioritize the high-risk component inside of the system. It is mostly happening that default or failure in the system occur due to more than three or four components. But there is a need to prioritize these components according to their operational mode, failure, and risk profile. In phase 3 we do risk analysis inspection, identify the relative maintenance program, and find best optimal solution for the system to be maintained, shown in Figure 42

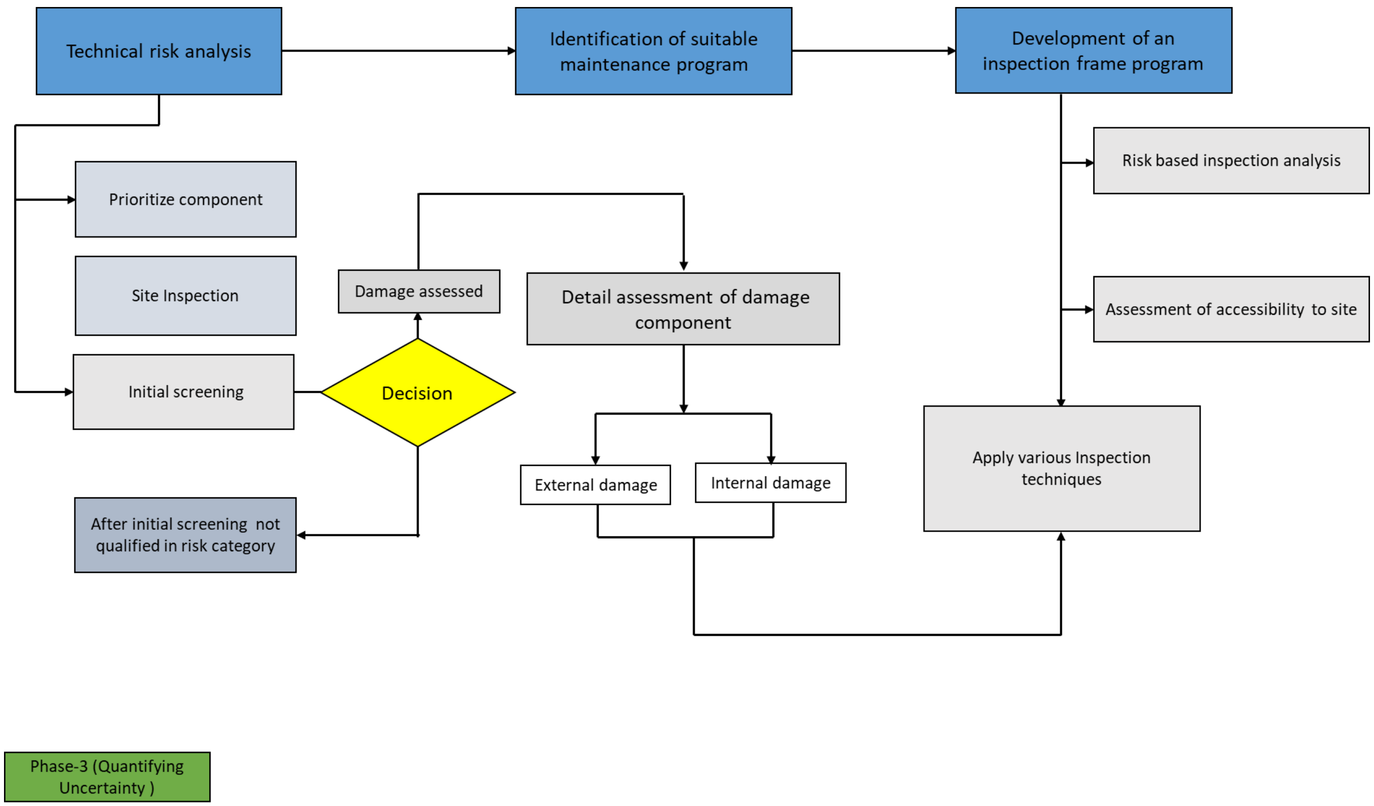


Figure 42: Framework -Phase 3

3.5.1 PRIORITIZTAIONS OF COMPONENT

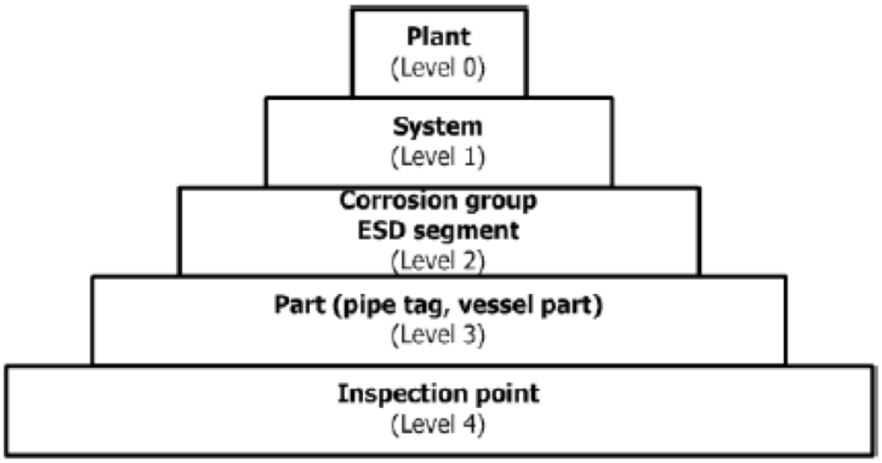


Figure 43: Hierarchy of Inspection Level (IdrissEl-thalji, 2019b)

The Figure 43 explains the level of screening and prioritization. At inspection point we can conclude the component adversity and their effect on the system. Parallel we also identify their risk attitude towards the system and comparative analysis with other components of the same system. In risk bases inspection mode, the working process have been divided into four categories:

1) Collection of information of the component and sub-component inside the default system
2) The initial screening assessment and analysis report.
3) The detail and thorough assessment of the components and sub-components.
4) The planning mode in which we categories the components according to their risk profile

Once the component has been passed through all these steps, the operator takes the decision either its viable to proceed and consider that component in highly risk category or we need further assessment and comparative analysis.

After the decision, if component falls in high division, we identify their relative degradation mechanism, their degradation history and consequences and damage assessment. According to the type and specialty of the component, the relevant data are checked, for example

1) Fluid properties
2) Measurement data
3) Material properties

4) Predictive analytics outcomes

3.5.2 EXTERNAL, INTERNAL DAMAGE & DEGRADATION MECHANISM

External sources of the issues are mostly considered by mechanical damage, environmental damage or corrosion and visible cracking while internal damage is caused by fluid inside of the system, for example erosion caused by fluid and particles. Also, the internal cracking because of continue fatigue load.

The detail of damage assessment, type of catastrophes and their relative degradation mechanism and types are already explained in literature review section 2.6.2.

3.5.3 INSPECTION TECHNIQUES AND TYPES

Following are the major techniques being adopt by operator during their inspection procedure. These techniques can be used according to functionality, accessibility to site and material properties of the component.

3.5.3.1 MAGNETIC PARTICLE INSPECTION

It is a non-destructive testing and one of the finest methods to detect the defect in near surface ferro-magnetic materials. During testing of the item, the suspension of magnetic particle being putted on the inspected item and later it can easily be seen the cracks that is appearing on the surface. Sometimes it is needed ultraviolet to see these top surface cracks.

3.5.3.2 RADIOGRAPHY

It is also a non-destructive testing method of inspecting hidden materials for hidden flows by using the ability of short wavelength electromagnetic radiations to penetrate through various material either an x-rays machine or different radio-active source. The source of photons mainly is CS-137 and CO-60. Radiography testing also use the gamma rays as a source to hit subjected inspecting material.

3.5.3.3 ULTRASONIC TESTING

The ultrasonic testing is also NDT technique which works on the principle of propagation and reflection of sound wave into the material. In this method, sound transmitter and receiver are being attached to the testing surface. As sound waves emit and touches the other of surface. If there is any cavity the sound waves will reflect earlier. The reflection size depends upon the size of the cavity inside of the component.

There is also numerous other technique that are being used during the inspection procedure of the system and equipment. The usability of the method depends upon the accessibility to the site, the behavior of material to specific method and adoptability of operator. The other major techniques that being used during inspection process are Eddy current, Neutron backscatter for detecting flooding in hollow meter, thermography, holography, and photogrammetry for measuring the distance between different object points.

3.5.4 RISK BASED INSPECTION ANALYSIS

It is the process of developing a systematic framework of inspection based on the information gathered about risk of failure. It requires qualitative or quantitative assessment of the probability of failure (PoF) and consequence of failure (CoF), associated and linked with inspected component or equipment (Vika, 2011). The Figure 44 shows that the level of risk can be defined by simply multiply CoF to PoF.

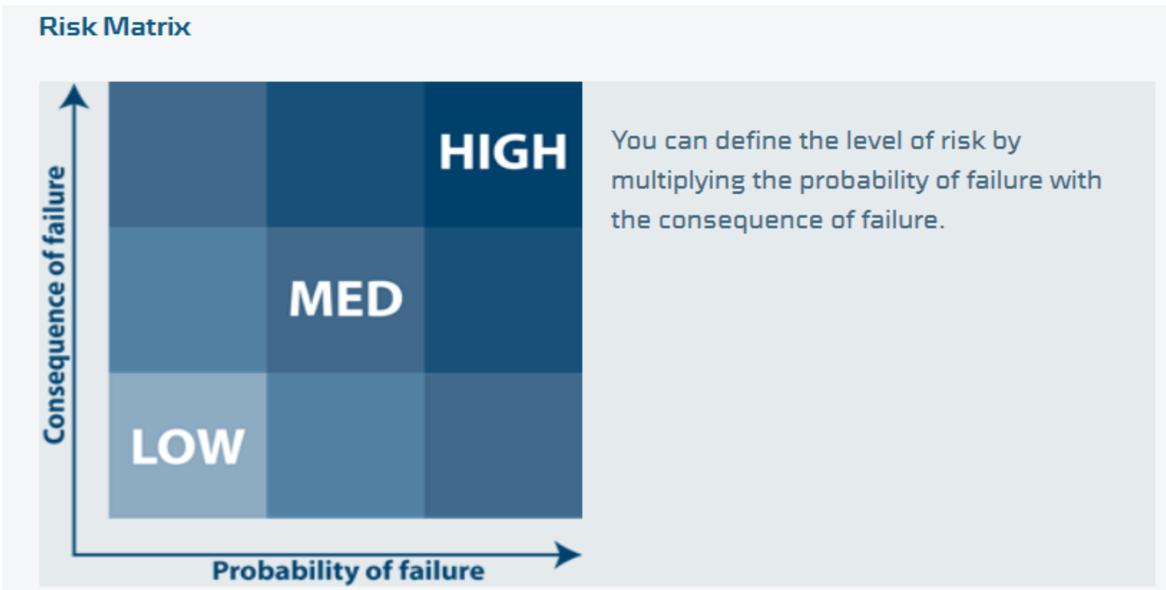


Figure 44: RBI Analysis (ForceTechnology, 2020)

Risk based inspection (RBI), is used to identify the risk drivers, risk profile of the component, risk presence in lifecycle of the equipment and incoming risk prediction. It quantifies the uncertainty by utilizing the probability of failure and consequences of failure. There are some major codes and standards related to RBI in petroleum industry API RP 580 and 581, ASME PCC-3 and RIMAP (inspectioneering, 2020).

The Table 10 describes the detail of all the standards with applicable relevant clause being used in the development of phase 3 of framework.

Table 10: ISO and Norsok Standards Phase 3

S/No	ISO 14224: 2016	ISO 20815:2008	NORSOK Z-2008
01	Uncertainty (clause 3.95)	Risk based inspection analysis (clause 1.15)	Inspection (Clause 3.1.21)
02	Critical failure (clause 3.9)	Risk (clause 3.1.44)	Risk Based Inspection (clause 3.1.37)
03	Degraded failure (clause 3.11)		Consequences Production (clause 3.1.7)
04			Hidden failure (clause 3.1.20)

3.6 Phase 4: Financial and Technical validation

The phase 4 of the framework is more about the cost structure and technical validation of the proposal with existing technologies and practices. There is a cost comparative analysis which validate the proposal cost and impact on the safety limits of the equipment. The Figure 45 illustrate the phase 4 of framework.

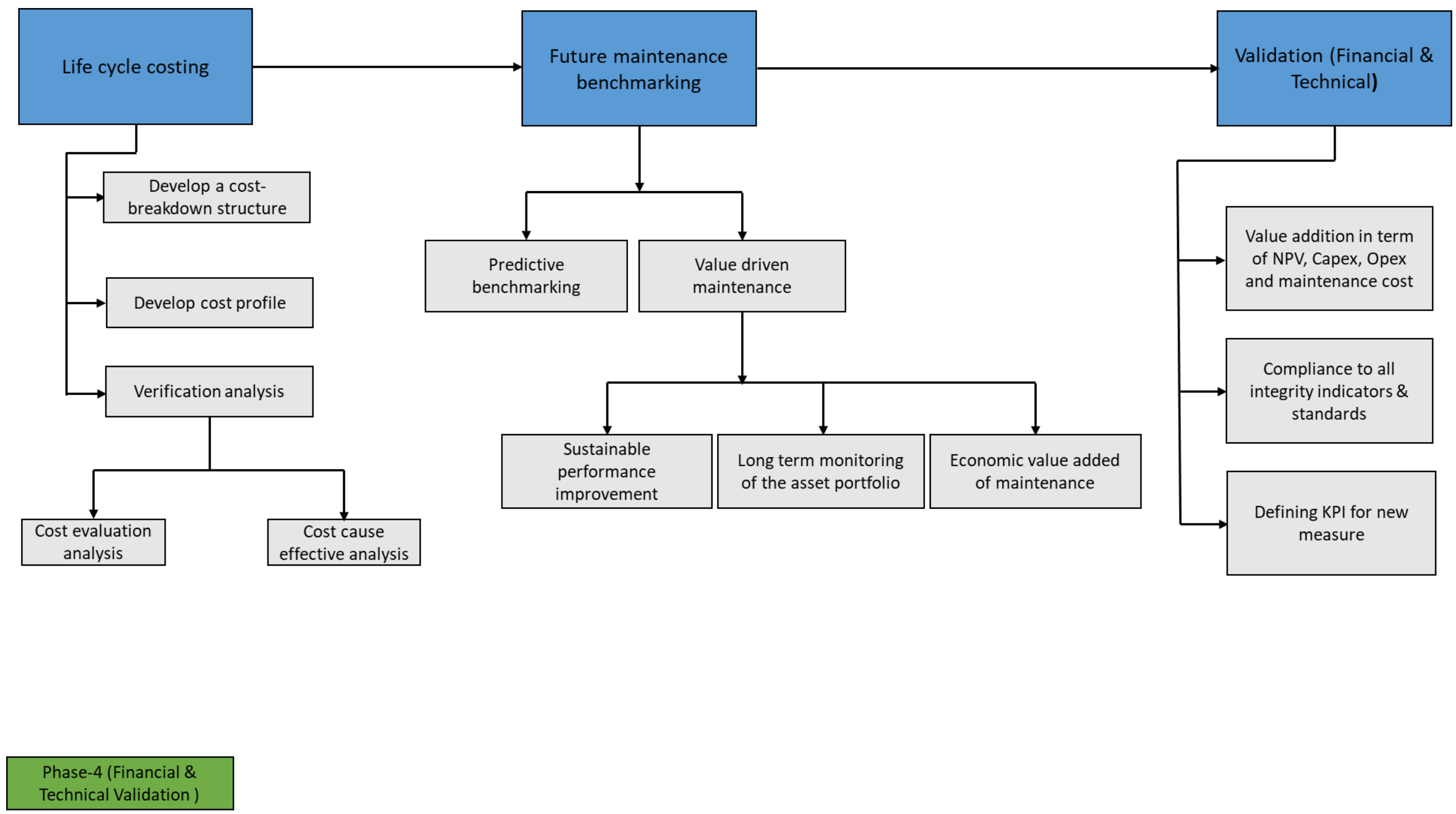


Figure 45: Framework-Phase 4

3.6.1 COST PROFILE AND COST BREAKDOWN STRUCTURE

It involves all the detail analysis of expenses and their breakdown into sub-system level. The activities have been divided into sub-section and then commercial assessment with all economical factor considered. The cost break down structure of a system and equipment includes following major categories (Jung & Woo, 2004).

1) Research and development cost
2) Production and construction cost
3) Operation and support(maintenance) cost
4) Management and disposal cost

While the cost profile includes following below major stages

1) Life cycle stage
2) Utilization stage
3) Labor and power supply stage
4) Sub-section elements of the system

3.6.2 COST BENEFIT ANALYSIS

The following steps involves in cost benefit analysis

1) Define the problem and identification possible alternatives
2) Identify the input and output of each alternatives
3) Value the cost of each preference
4) Comparison of net cost and benefit of each alternative
5) Identification of best option

3.6.3 VALUE DRIVEN MAINTENANCE (VDM)

Maintenance add economic value to a venture by distributing maximum availability at minimum possible cost. Over the time, the cognitive thinking of decision maker has been shifted to view maintenance as value driver instead of cost-based reasoning. The value driven maintenance is not a maintenance but its philosophy and decision to perform VDM is purely depends upon the cost benefit analysis. It requires a fine balanced between upgraded reliability and cost of maintenance (fiix, 2020).

3.6.3.1 VDM FORMULA

The Figure 46 illustrate the VDM formula along the terminology used in maintenance process of the system.

$$PVPM = \sum \frac{(FSHE,t) * [(CFAU,t) + (CFCC,t) + (CFRA,t) + (CFSHE,t)]}{(1 + r) * t}$$

PVPM	=	present value potential of maintenance
FSHE, t	=	SHE factor in year t (% compliance with SHE regulations)
CFAU, t	=	future free cash flow in year t from asset utilization
CFCC, t	=	future free cash flow in year t from the cost control
CFRA, t	=	future free cash flow in year t from resource allocation
CFSHE, t	=	future free cash flow in year t from SHE
r	=	discount rate

Figure 46: Value Driven Formula (fiix, 2020)

3.6.3.2 VALUE ADDITION OF INTELLIGENT MAINTENANCE

The Figure 47 shows how the operational cut and maintenance cost can make a difference in term of profit of the company. It also shows different level of profit in consideration of losses saving, maintenance cost saving and fixed saving i.e. manpower and routine checkups.

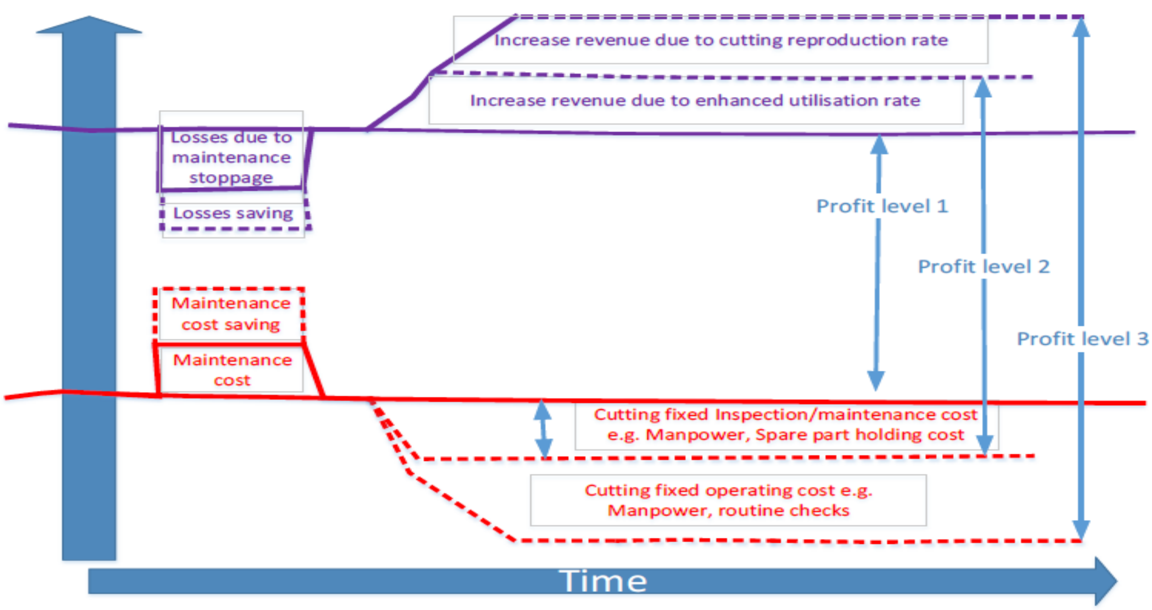


Figure 47: Maintenance Cost and Benefit (idrissEl-thalji, 2019a)

The following below are the key benefits of intelligence maintenance in term of revenue and LE of the system. It reduces the ageing mechanism and enhance the life of equipment as well as safety limits of the system.

1) Increased the production revenue
2) Enhanced the utilization and performance rate of the system
3) Reduced planned maintenance event
4) Reduced the level of operating crew, excessive care, auxiliary equipment, spare [part inventory and reduce the level of supportive maintenance activities.
5) It increases the lifetime revenue and reduce the maintenance cost by preventing failure

The Figure 48 illustrate the production timeline of the system and how maintenance events influence the performance, functionality, quality, and production availability.

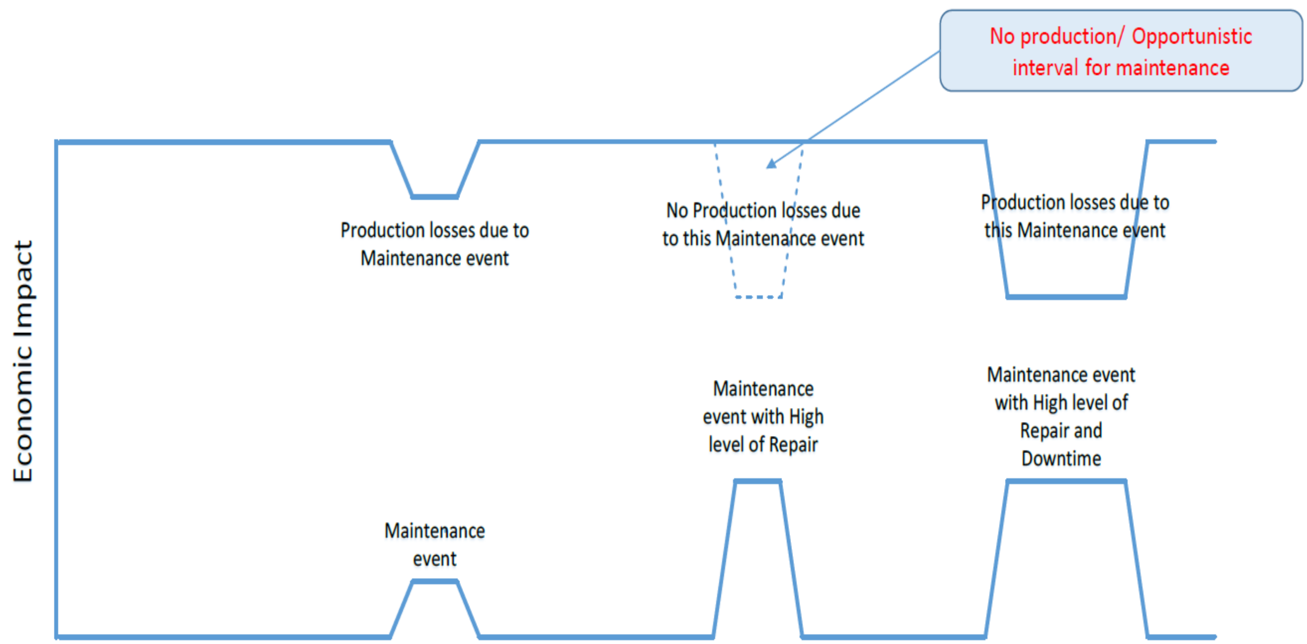


Figure 48: Maintenance Timeline for 20 Years (idrissEl-thalji, 2019a)

3.6.4 PREDICTIVE BENCHMARKING

After applying and gathering information from predictive analytical techniques, future prediction with precise benchmarking is straightforward and accessible. During the process of predictive benchmarking not only the data gathered from predictive analytical methods applies, but also the statistics being collected from reliability, availability, operability, and maintainability operations are used. In O&G industry predictive benchmarking helps in optimization and prognosis of almost all the upstream, mid-stream and downstream operations. The Figure 49 illustrates the main area of O&G activities in which predictive benchmarking plays a key role.

Figure 49: Predictive Benchmarking & O&G Activities

The Table 11 illustrates the relevant standards and applicable clauses being used in phase-4 of the framework.

Table 11: Standards-Phase-4

S/No	ISO 14224:2016	ISO 20815:2008	NORSOK Z-2008
01	Predictive maintenance (clause 3.77)	Life cycle cost analysis (clause I.19)	Performance Standards (clause 3.1.30)

4. A DEMONSTRATED CASE FOR APPLICATION OF THE SUGGESTED LE FRAMEWORK

The application and validation of suggested framework has been done with following below assumed postulates and parameters.

4.1 LIMITATIONS

Due to Covid-19, the practical movement was restricted and difficult to attain the data from the companies. So, keeping in view all these uncertain parameters, the suggested framework has been executed by a demonstrated case scenario of static equipment and all the values are being assumed.

4.2 SYSTEM DESCRIPTION & ASSUMPTION

The system requires 20 years of cost effective and technically viable maintenance plan. It is assuming that the most critical component or equipment inside of that system is pipe. All other component of the system is working smoothly and has extended work life of 20 years. It has also been assumed that there are no mitigation measures required.

The facility extended life: 20 years

All other assumption and detail have been described in table 12.

4.3 OBJECTIVE

Enhancing the life and safety limits of Equipment by optimizing the maintenance needs and predictive benchmarking.

4.4 DETAIL ASSESSMENT

The Table 12 shows us the detail of assumed postulates about the system and equipment

Table 12: Assumed Postulates

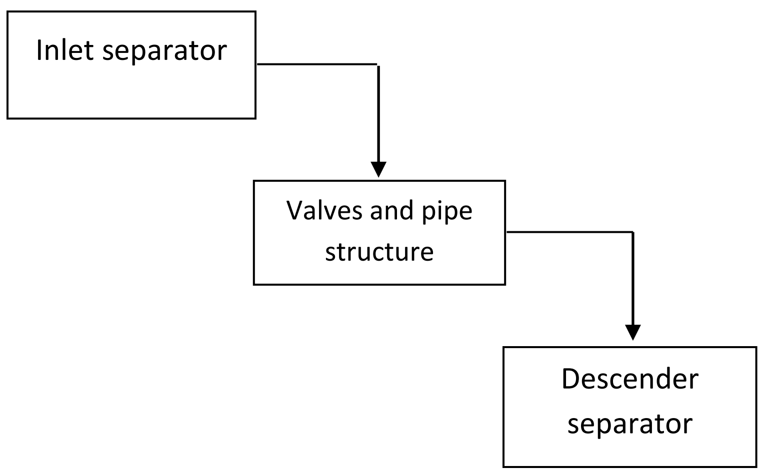
S/NO	Description	Assumptions
01	System	Produced water system
02	Equipment	Pipe
03	Degradation mechanism after history evaluation	corrosion
04	Inspection Technique	Ultrasonic (UT)
05	Existing maintenance program	Preventive maintenance
06	Operators comments	No up thrust and rotation of equipment While leakage occurring & corrosion observe
07	Mitigation measure	Not required

08	Secondary assessment (RUL)	Not required
09	Further assessment	Not required
10	Maintenance needs	Yes
11	Compliance to all integrity indicators	Yes
12	Initial damage ($\mathbf{D_o}$)	0.02 mm
13	Load accumulation factor (C)	0.5 (can be vary as per loading condition)
14	Elements in pipe	Water, gas, and sand
15	Expected lifetime	20 years

The demonstrated case is simplified with assumed value of detail assessment. After the evaluation process the equipment has been qualified for LE and it requires maintenance optimization to enhance the life of equipment and validate the best maintenance interval. According to framework the first step in phase 2 of maintenance process is defining the physical and functional architecture of the equipment.

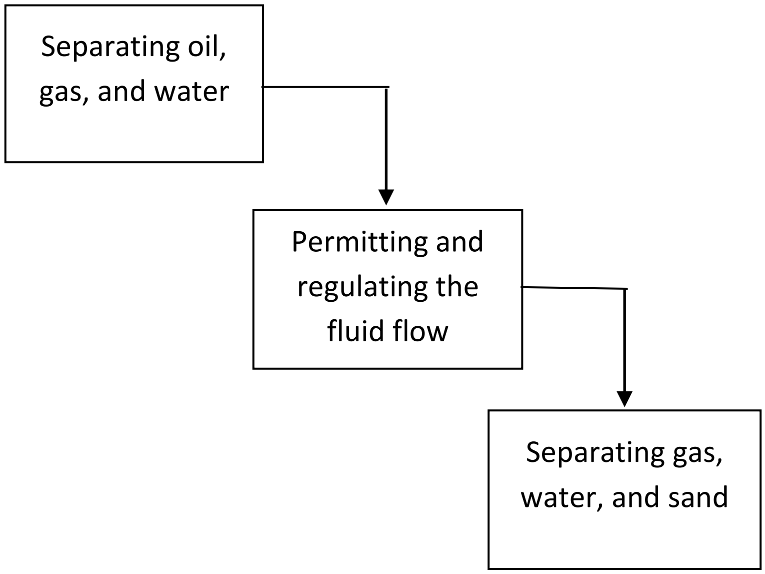
4.5 PHYSICAL ARCHITECTURE OF THE EQUIPMENT

The physical architecture of assumed equipment has been described below



4.6 FUNCTIONAL ARCHITECTURE OF THE EQUIPMENT

The functional architecture of the equipment illustrated below



The fluid with mixture of oil, gas, water, and sand comes into inlet separators that further distributes the fluid into three different compartments and sections. The water and sand together go for further treatment into de-sander which separates the sand, gas, and water.

4.7 SYSTEM OF CONTEXT OF THE EQUIPMENT

The system of the context of the equipment has been described below in Figure 50

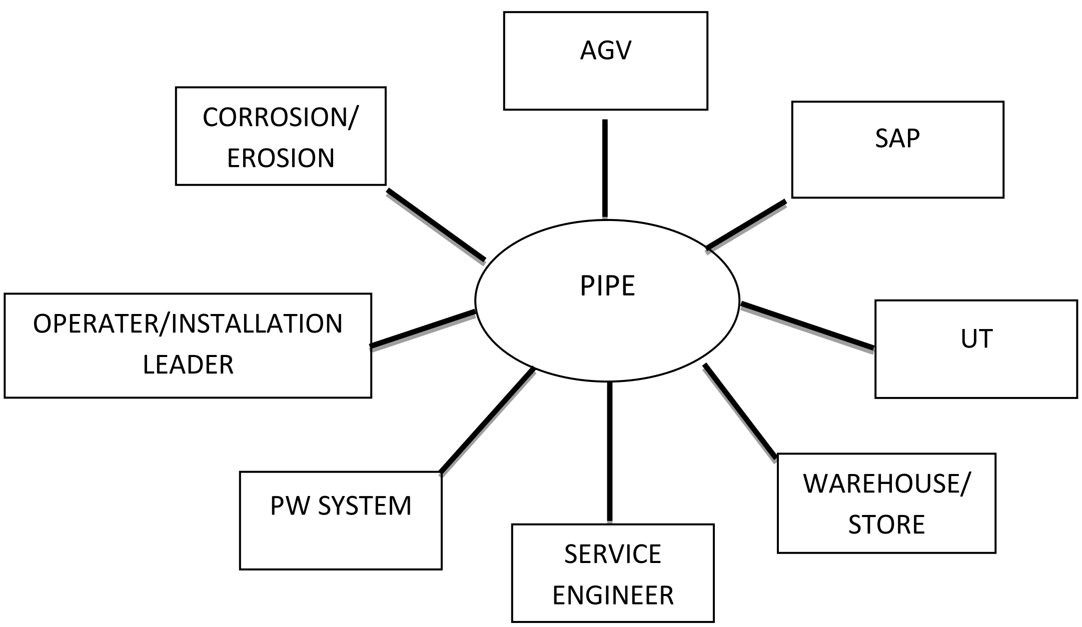


Figure 50: SOS of Pipe Structure

4.8 RELIABILITY AND MAINTENANCE DATA

In Table 13 all the relevant failure modes, failure causes and failure mechanism described.

Table 13: Reliability and Maintenance Data

S/No	Maintainable item	Failure mode	Failure mechanism and causes	Deteriorating failure rate	Detectability of failure mode	Discipline
01	PIPE	Break down	Mechanical failure, overheating, breakage, plugged and alignment failure	N/A	Observable	Mechanical
02		External leakage	General leakage and wear	N/A	Observable	Mechanical
03		Vibration	Vibration, looseness, and cavitation	N/A	Observable	Mechanical
04		**Structure deficiency**	**Leakage, corrosion, and erosion**	$\frac{\Delta D}{\Delta t} = C \cdot D$	**Observable/monitored**	**Mechanical and Operational**
05		Minor in service problems	Mechanical failure, instrument failure, material failure and clearance/alignment failure	N/A	Observable	Mechanical

The collection of reliability and maintenance data mostly occur after applying failure analysis techniques, while in this case the deteriorated rate is considered as mathematical model with variables that changes with time domain. Where D is damage size, C is random variable representing load accumulation and assumed exponential distribution of 0.5. While the initial damage size is $\mathrm{D_o} = 0.02$.

The next step in the framework is to go into phase 3 and to prioritize the high-risk component, so we assumed the pipe between inlet separator to De-sander is the damage section. The already existing maintenance program was preventive based approach and for future surveillance and inspection of pipe corrosion mobile robotic system with embedded Arduino card can be used.

The section 4.8 analyzes the pipe and make the basis for comparative analysis. The maximum damage size at which corrective maintenance will be occur is 1, while the loading factor is 0.5, the lifetime is 20 years.

4.9 RISK BASED INSPECTION

The high-risk component is prioritized, and it go for further risk analysis techniques, considering probability of failure and consequences of failure. The general damage size of pipe is calculated by following equation, adding the value of initial damage size and the rate of deterioration.

The damage size calculated each year by:

$$\mathrm{D(t + \Delta t) = D(t) + \frac{\Delta D}{\Delta t} \cdot \Delta t}$$

Failure occur when damage size exceeds 1.

The deterioration model is simulated by running 10^3 Monte Carlos simulations in MATLAB.

The expected number of corrective maintenance actions for 20 years lifetime is:

With $\mathrm{E[n_{failures}]}$ is expected number of failures.

$$E[n_{failures}] = \frac{\sum_{i=1}^{20} number\ of\ failures\ in\ i^{th}\ year}{total\ number\ of\ simulation} = 1.2260$$

The section 4.10 illustrates the utilization of three different techniques and their comparison in connection to cost and technical enhancement

4.10 COST COMPARATIVE ANALYSIS AND PREDICTIVE BENCHMARKING

The cost analysis of corrective, preventive and predictive maintenance has been calculated by following below equations

4.10.1 CORRECTIVE MAINTENANCE

Corrective maintenance is a maintenance performed to recognize and rectify the fault in the equipment so it can perform or restored to an operational condition (OPL, 1991).

The total costs of corrective maintenance during design lifetime of 20 years are given by:

$$\mathrm{C_T} = \sum_{\text{all failures}} (\mathrm{C_{repair}} + \mathrm{C_{loss}}(\mathrm{T_{repair}}))$$

With $\mathrm{C_{repair}}$ *is repair + crew + transport cost;* $\mathrm{C_{loss}}$ *is lost energy per hour while system is not working ;* $\mathrm{T_{repair}}$ *is repair and transport time;*

The total expected cost of corrective maintenance is approximated as:

$$\mathrm{E[C_T]} = \mathrm{E[n_{failures}]} \cdot (\mathrm{C_{repair}} + \mathrm{C_{loss}}(\mathrm{T_{repair}}))$$

The assumed value for corrective actions is described below

$\mathrm{C_{repair}} = 275000$*,* $\mathrm{C_{repair}} = 125\text{euro/h}$, $\mathrm{T_{repair}} = 20$ *hour*

So, by putting the values in below equation and adding the value for expected no of corrective maintenance actions in 20 years

The expected costs for a corrective maintenance:

$$C_{CR} = \sum_{all\ failures} (C_{repair} + C_{loss}(T_{repair})) = 3.40215 \cdot 10^5\ euros$$

The total expected costs for corrective maintenance:

$$E[C_T] = E[n_{failures}] \cdot (C_{repair} + C_{loss}(T_{repair}) = 1.2260 * 3.40215 \cdot 10^5 = 4.17 \cdot 10^5\ euros$$

4.10.2 PREVENTIVE MAINTENANCE

Preventive maintenance is maintenance that regularly performed on a system and equipment to reduce the probability of failure (Patton, 2004). After calculating corrective maintenance cost of the equipment, 10 different sub-intervals have been assigned for preventive actions. The table 14 shows the cost for each preventive interval and table 14 explains the corrective cost needed during these intervals. For example, the interval 3, means preventive maintenance after every 3rd year and during that time corrective cost will be 2775 euros. After calculating and analyzing for 10 intervals, the best optimal cost interval including both preventive and corrective maintenance costs is shown in figure 49.

The preventive maintenance cost for each preventive repair interval strategy can be calculated as:

$$C_{PR} = \sum_{all\ repair} \left(C_{repair} + C_{loss}\left(T_{repair}\right)\right)$$

Assuming the repair time of 20 hr. and preventive maintenance cost, including the boat cost is 15,000 euro. Each preventive action reduced the damage size to 0.02 mm.

The preventive costs for different preventive intervals are shown in Table 14 below. Here for interval 1 year, 19 preventive repairs are considered as year 20 is final year.

Table 14: Preventive Repair Cost

Interval(years)	Preventive repair cost(euros)	Interval(years)	Preventive repair(euros)
1	$\mathbf{3.9568 \cdot 10^4}$	6	$\mathbf{2.6530 \cdot 10^4}$
2	$\mathbf{3.5298 \cdot 10^4}$	7	$\mathbf{1.9390 \cdot 10^4}$
3	$\mathbf{3.3723 \cdot 10^4}$	8	$\mathbf{2.3398 \cdot 10^4}$
4	$\mathbf{2.7738 \cdot 10^4}$	9	$\mathbf{2.5340 \cdot 10^4}$
5	$\mathbf{2.2313 \cdot 10^4}$	10	$\mathbf{1.3003 \cdot 10^4}$

The expected corrective repair cost with different preventive repair intervals is shown in Table 15 below:

Table 15: Corrective Repair Cost with Relevant Interval

Interval(years)	Corrective repair cost(euros)	Interval(years)	Corrective repair(euros)
1	$\mathbf{0}$	6	$\mathbf{7.1873 \cdot 10^4}$
2	$\mathbf{0}$	7	$\mathbf{9.2963 \cdot 10^4}$
3	$\mathbf{2775}$	8	$\mathbf{7.6035 \cdot 10^4}$
4	$\mathbf{18870}$	9	$\mathbf{8.990 \cdot 10^4}$
5	$\mathbf{4.578 \cdot 10^4}$	10	$\mathbf{1.4125 \cdot 10^5}$

The total expected cost for each preventive interval can be estimated as:

$$E[C_T] = E[C_{PR}] + E[C_{CR}]$$

The Figure 51 illustrates the expected total cost as function of preventative repair intervals.

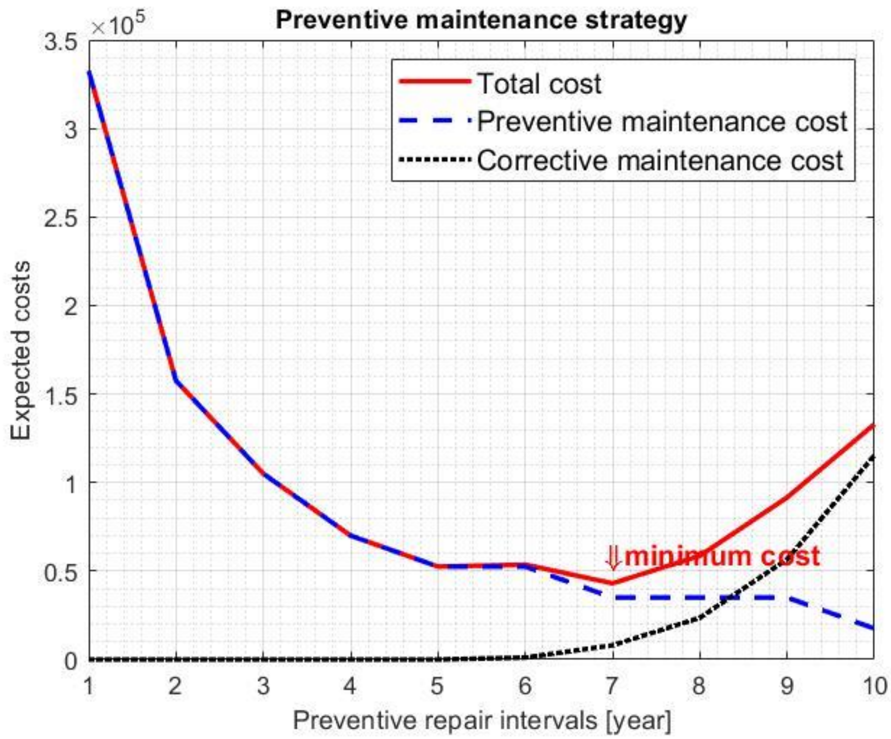


Figure 51: Preventive Maintenance Cost

The Figure 51 clearly shows that the optimal maintenance interval is 7th year with minimum total expected cost. It means that during the lifetime of equipment i.e. pipe, after every 7th year preventive maintenance required in consideration of cost effectiveness and technical requirements.

4.10.3 PREDICTIVE MAINTENANCE

Predictive maintenance is a method to predict incoming failures in the equipment, it also points the future failure points with precise time interval. This advance approach reduces the maintenance cost and minimized the downtime of the system and enhanced the life, safety limits and net value of the equipment (Mobley, 2002).

To execute the predictive maintenance process, continues surveillance actions required. This surveillance can be done by installation of sensor and in some cases fixed Inspection can also be performed. The total costs of a sensor (including management) are 1000 euro.

During the predictive maintenance strategy, if the damage is detected i.e. damage is more than 0.2, then preventive repair is performed, and it reduced the deterioration to initial damage size i.e.0.02. While if damage size is greater than 1, then corrective repair is performed.
The total expected cost in predictive maintenance-based strategy for each interval is:

$$E[C_T] = E[C_{PR}] + E[C_{CR}] + E[C_I]$$

The Figure 52 illustrates the expected total cost as including all three different strategies

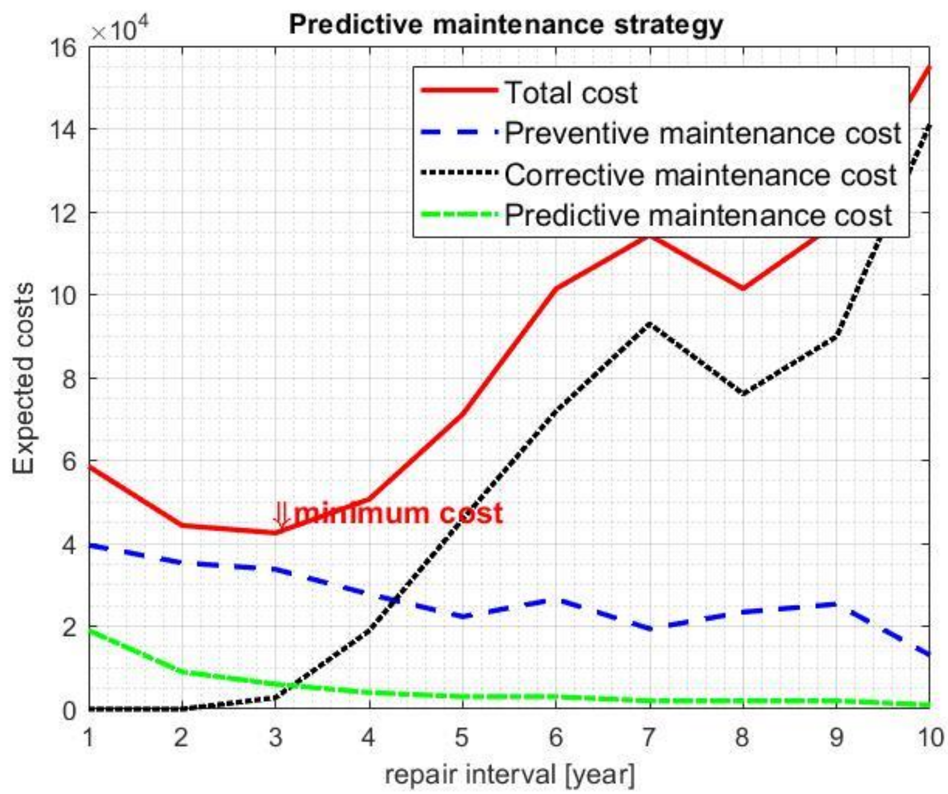


Figure 52: Predictive maintenance strategy

The strategies described in this exercise i.e. corrective maintenance , preventive maintenance , and predictive maintenance have different optimal costs associated as shown in Table 16.

Table 16: Comparative analysis

Strategy	Total expected cost (euros)	Interval year
Corrective maintenance	$\mathbf{3.44 \cdot 10^5}$	--
Preventive maintenance	$\mathbf{4.97.10^4}$	7th year
Predictive maintenance	$\mathbf{4.59 \cdot 10^4}$	3rd year

The results show that predictive maintenance strategy is the most cost-efficient strategy as expected.

The predictive maintenance repair strategy provides additional information about the structure thus doing repair before structure goes into failure while the cost of inspection or sensor is very less.

The corrective maintenance -based strategy is always the worst due to failure and downtime costs while preventive repair strategy shows promising results.

The optimal maintenance interval varies as accumulation load factor (C) changes, putting the value of C : 1 , the Figure 53 and Figure 54 shows the optimal maintenance interval in consideration of cost and technical measures shifted to every 4th and 2nd year for preventive and predictive maintenance.

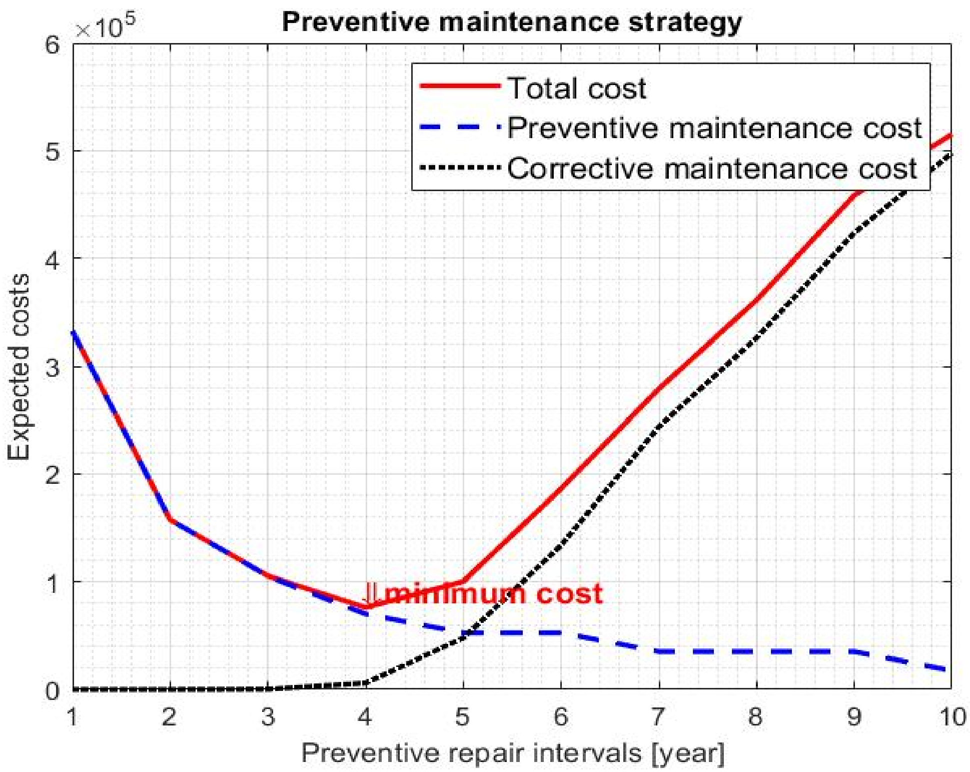


Figure 53: Preventive Maintenance with C: 1

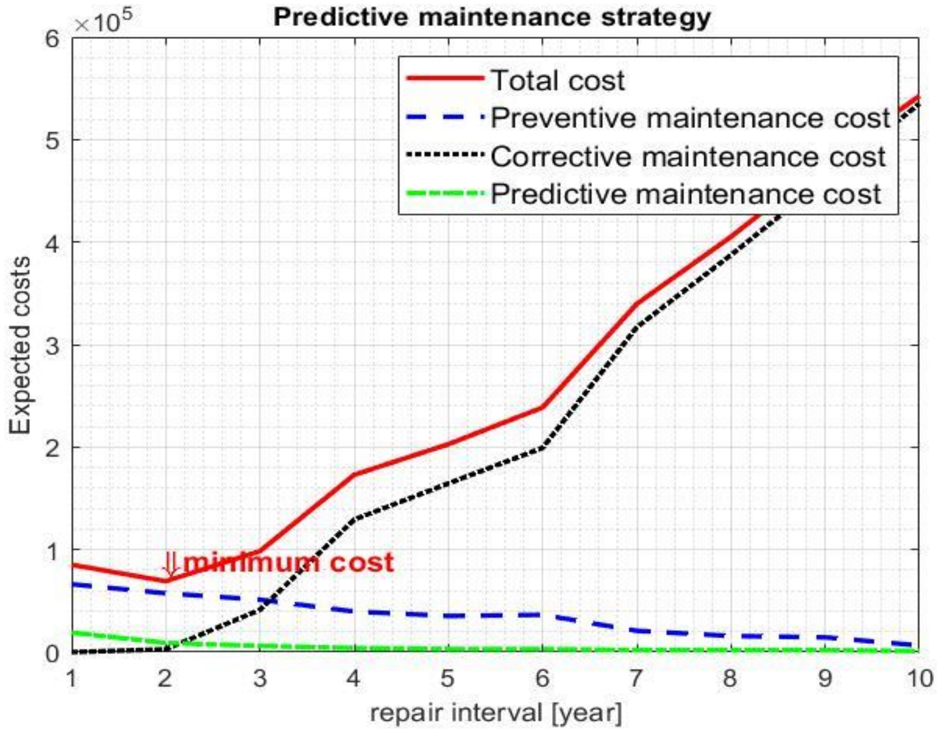


Figure 54: Predictive Maintenance With C: 1

Assume the value C: 0.75 as shown in Figure 55 and Figure 56.

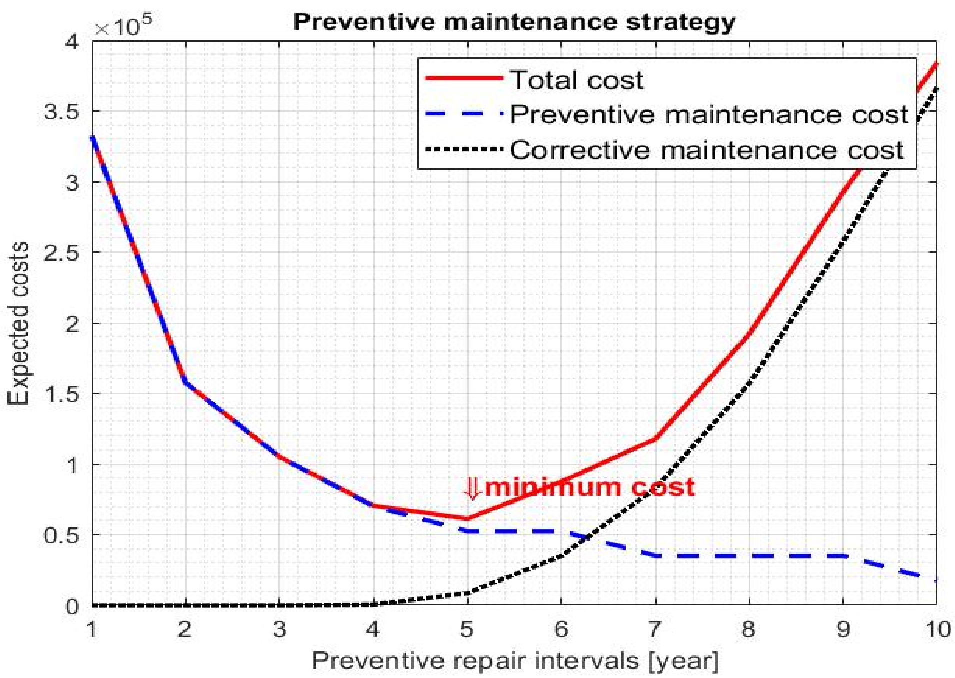


Figure 55: Preventive Maintenance With C: 0.75

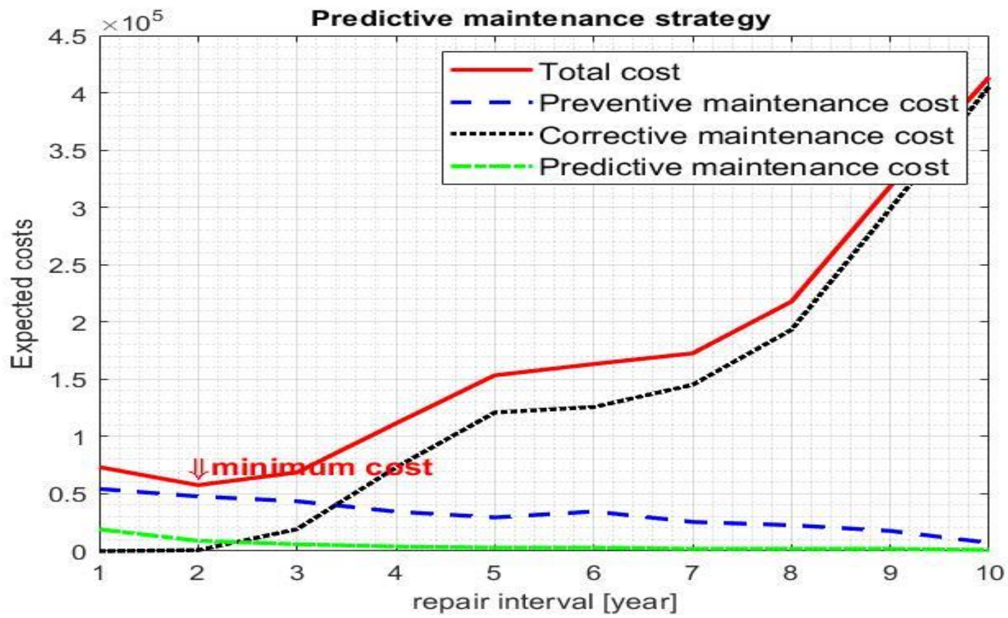


Figure 56: Predictive Maintenance C: 0.75

4.10.4 RESULTS

The Table 17 shows the detail of results at different loading condition.

Table 17: Results

S/No	Accumulation load factor (C)	Preventive optimal interval	Predictive optimal interval
01	0.5	Every 7th year	Every 3rd year
02	0.75	Every 5th year	Every 2.2 year (approx.)
03	1	Every 4th year	Every 2nd year

1) The optimal predictive maintenance interval is cost effective and technically validated at different loading condition. It enhances the life and safety limits of equipment by 20 years. (This is the minimum intervals for maintenance required according to various loading conditions during the lifetime of equipment).
2) The fixed surveillance cost in case of predictive maintenance is manageable and efficient. It also gives timely result regarding deterioration of the equipment.
3) By the variation of accumulated load factor (C), the optimal interval shifted. As load increase, the optimal predictive repair interval decreases, and it increases the overall cost of equipment maintenance but validate the technical requirement of the equipment.

5. DISCUSSION

This section looks at the overall work that has been done in this thesis. It also highlights the future prospect of the work and learning outcomes. Identifying the opportunities and challenges faced by modern day industry.

5.1 SUMMARY

The main aim of this thesis was to identify the challenges that are faced by O&G industry in LE process. It is also analyzed and classified a relation among maintenance needs, operational requirements, and their consideration in LE phenomenon. The development of the framework set a roadmap for adoption of LE mechanism aligned with financial and commercial aspect of the offshore system.

The theoretical section starts with prospect of O&G in NCS and then it highlights the major challenges faced by modern day industry. The explanation steps lead to an operational and engineering risk that are associated with drilling process and their connectivity to financial uncertainty in the world. Onward the extensive and thorough study were carried out which includes the ageing mechanism and major hazards linked to it and work has been done on mature field and their future prospect in North Sea. The ageing process is widely spread topic. The thesis is covered mainly by the major hazards, associated risk, mitigation action and their mainframe elements i.e. the obsolescence, human and organizational factor, and material degradation phenomenon. At the end of the literature review section, the LE process is illustrated and the key factors and boundaries of LE has been explained in detail along with their connectivity to end life management issues. The further study was carried out in describing the role of digitalization, reliability and integrity factor, commercial prospect, and technological acceptance in the process of LE.

After the identification of the LE and ageing perimeters, the framework was developed. The framework provides structured and comprehensive approach in analyzing the offshore system and equipment in end life management scenario. The framework further consists of four phases which started from the LE assessment procedure and it validated either the system was qualified for LE process or it required further re-evaluation. Before qualifying for LE, the decommissioning aspect was also ruled out. In phase 2 and 3 risk analysis approach was carried out which considered all the maintenance needs of the system and characterized the major steps required in operational process. The last phase validated the financial portion of the maintenance action in consideration of LE process. All the phases and elements that are being used inside of the framework are described according to ISO and NORSOK standards.

The last section of thesis was the application of suggested framework and it demonstrated the practical case scenario with assumed value. This part ended with cost comparative analysis and predictive benchmarking of the offshore system.

5.2 MY LEARNING

The thesis work increases my capacity to integrate expertise and analyze different technical solutions. It also enhanced my capability to plan and to conduct different task independently. Expand and upsurge my capacities and capabilities in different research related developments. The framework phase development boosted my cognitive behavior and helped me in understanding the significance of sustainable development in consideration of end life management scenario. At the end, the extensive research work provided great support in understanding the offshore O&G facilities, their economic prospect, maintenance aspect inline to LE and ageing mechanism.

5.3 CHALLENGES

In offshore O&G industry the LE process is a complex phenomenon facing various challenges in development procedures. The industrial operational activities should be carried out in consideration of reliability, safety, and integrity plans. The present developed framework is the concept of maintenance needs and operational requirements of the system in lined to LE process.

The data collection and information gathering of the mature field is one of the daunting tasks. In history evaluation stage of the framework, the clarity regarding the information, provided the foundation in decision making process of LE. But lack of integrity management practices affected the information gathering procedure, failure data collection and maintenance history of the equipment.

The reluctance in adoption and acceptance to advance digital technologies and ageing human factor, could have affected the execution parameters in phase 4 of the framework. The practical demonstration case of dynamic equipment was also a challenging task. The deteriorating rate and accumulation load factor varied with time domain and it required demanding effort to make simulation and future projection of the maintenance actions.

To understand core constraints and fundamental aspects of the LE topic, thorough and extensive workout required. The limited familiarity of the author to practical experiences of LE, the hard time of pandemic, lack of excess to student library and maintaining the balance between ambition and optimism was a challenging task. Additionally, the availability of limited academic literature made the topic more demanding and time taking. Out of all these challenges the expert opinion was a valuable source of information, certainty, readiness, and inspiration.

5.4 RECOMMENDATION FOR FUTURE WORK

The looming global economic uncertainty and shifting paradigms to renewable energy and electrification hamper the new investment in O&G sector. Considering all these parameters, companies are taking steps to boost investment in LE process. The research in LE is still in early stages and there is a greater room for further research. In suggested framework some areas have been identified as a potential material for future exploration and analysis.

The utilization of predictive analytical techniques and their outcomes can have greater impact on maintenance activities of the system. In predictive maintenance, work can be done to utilize the digitalization and industry 4.0 concept. The installation of sensors on faulty equipment can reduce the cost and remove the numerous uncertain factors i.e. human resource, environment, system breakdown and transportation cost.

During the history evaluation and detail assessment of the system, mitigation steps can be taken to remove the fault from the equipment. These measures can enhance the life and safety limits of equipment and it also reduce the cost of maintenance and operation.

Further work can be done on the validation of the framework by taking the demonstration case of dynamic equipment. Each phase of framework can be sublet further into sub-stages in consideration of life extension approach. The general static case can further be validated by adding more failure modes and failure mechanism and their overall impact on LE.

Due to Covid-19 the practical access to companies and interaction with the maintenance engineers and operation team was not possible. But in future, the framework can be validated by comparing the existing model of end life management in services companies. The improvement in each stage can be done and there is room for further enhancement or addition of elements in each phase of suggested framework.

6. CONCLUSION

The O&G industry due to economic uncertainty reaches to a point where technology and market benefits are unlocking the greater opportunities in enhancing the life of the existing fields. Currently the optimization of existing operational facilities and asset utilization becomes the widely accepted practice and strengthen by financial prospect. This drive the researcher to build the optimization and assessment model in consideration of end life management scenario.

The framework was suggested to optimize the maintenance needs and operational requirement of the offshore system inline to life extension scenario. The model assesses the potential for LE considering all the risk factors, asset maturity, deterioration and degradation mechanisms, remaining prospect of reservoirs and commercial viability of the system. The model adopts the approaches of both qualitative and quantitative aspect while the expert opinion was valuable in stated constraint of data availability.

The framework consists of four phases, the initiation stage involves the detail assessment and history evaluation of the system or equipment. This phase mainly involves the collection of information and their analysis according to advance adopted methods. Result of this phase leads to process of LE or either decommissioning. After qualification for LE, the second stage is to scrutinize the system either it needs mitigation measures or maintenance requirement. The collection of reliability and maintenance data and implication of various analysis techniques put forward the system into technical risk analysis phase, in which all components have been prioritize according to their risk attitude and uncertainty has been quantified. The phase 4 involves the future predictive benchmarking, cost comparative analysis with existing practices and their financial viability.

The developed framework provides a comprehensive reasoning and viewpoint to LE, by covering almost all the aspects of safety integrity, reliability, maintainability, risk, and financial viability. The framework is acknowledging adequately the modern industry needs and helping the asset managers in decision support models for LE

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