Amanda Rossi

A CONDITION BASED, RISK ANALYSIS AND LIFE CYCLE ORIENTED APPROACH FOR LIFE EXTENSION OF FPSO UNITS

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Amanda Rossi

NTNU
Norwegian University of
Science and Technology
Faculty of Engineering
Department of Ocean Operations and Civil Engineering

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Amanda Rossi

Ship Design
Submission date: June 2020
Supervisor: Henrique M. Gaspar
Co-supervisor: Odd Weisæth

Norwegian University of Science and Technology
Department of Ocean Operations and Civil Engineering

NTNU
Norwegian University of Science and Technology

MSc SHIP DESIGN

A CONDITION BASED, RISK ANALYSIS AND LIFE CYCLE ORIENTED APPROACH FOR LIFE EXTENSION OF FPSO UNITS

Candidate: 10011
Amanda Caroline Rossi

Aalesund, June 2020

NTNU – Ålesund
Norwegian University of Science and Technology

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Department: Ship Design

DEVELOPMENT OF A METHODOLOGY FOR ASSESSING REDEPLOYMENT OF FPSO UNITS: A LIFECYCLE AND RISK ANALYSIS APPROACH

Introduction

The petroleum and energy industry is responsible for exploration, extraction, production, processing and transportation of oil and natural gas. Today, the oil industry is one of the most important stakeholders in the maritime world, responsible for a huge and complex supply chain that involves from oil rigs and offshore units, to shuttle tanks and service vessels. It is moved by a cyclic economic behavior, historically experiencing ups and down and as in 2019, the industry is recovering from the 2014 oil crisis.

With the new "boom" of the offshore industry, different needs will emerge – new oil fields will be explored, and some will have their exploration life extended. There are different types of offshore facilities, from fixed platforms to FPSO's (Floating, production, storage and offloading units – Figure 1). The need for vessels to supply this demand will come up, creating a great opportunity for the FPSO market. It is necessary to evaluate the fleet already in operation to understand the possibilities of redeployment and life extension, i.e. moving the unit to another field after the oil field has reached it exploration life or keeping at the same field for longer than anticipated.

Figure 1 – Ship shaped FPSO (Courtesy of Altera Infrastructure).

Motivation

Redeployment is beneficial as there is no need to build a new vessel, that would deal with issues from concept design to shipbuilding. Yet, it is not a straightforward process, as a study considering redeployment must be performed in order to understand if the unit is a fit or not for the new field. For the successful redeployment of an asset, the whole unit lifecycle shall be considered and optimized,

FPSOs are complex system and a holistic methodology that understand all the requirements in redeployment is needed in order to create a much more optimized process that consider operational costs, risk analysis and life extension scope. Understanding what the critical systems and key drivers are when relocation the asset can give input to a better operational scheme. Most companies optimize their performance for the current operation, but lack to fully understand what can be done in long term maintenance strategy that can save thousands of dollars during the redeployment procedure.

Scope
This thesis shall propose a methodology for assessing redeployment of FPSO units to new oil fields. It shall begin by understanding lifecycle management of FPSOs and identifying the critical systems guiding redeployment process, which shall be limited to the 10-15 most important ones. Then, a procedure to acquire condition status and future scope of work for the units shall be created. The qualitative model for condition status shall be processed into a quantitative model, possibly studying the availability of creating life prediction models for the key parameters. A risk analysis shall be performed, developing a risk model for each of the critical systems identified before. Risk control options and cost assessment is to be carried out to define whether the unit is suitable for redeployment or not. The methodology shall be tested out in a fictional vessel. The thesis is limited to field specific changes related to the redeployment of the FPSO. Analysis for field specific scope of work and changes, for either marine or topside systems, is not covered by this thesis.

Methodology
The thesis methodology consists of literature review, concept definition and tools development. It is a theoretical thesis based on information available on asset operation condition. The tools to be used will consist primarily from Office365.

Objectives
The objective of the thesis is to present a methodology to assess the possibility of redeployment of FPSO units. It shall consider the asset status, possible scope of work for extending operational life, and the risks associated with it. This shall be made by answering the following research questions:

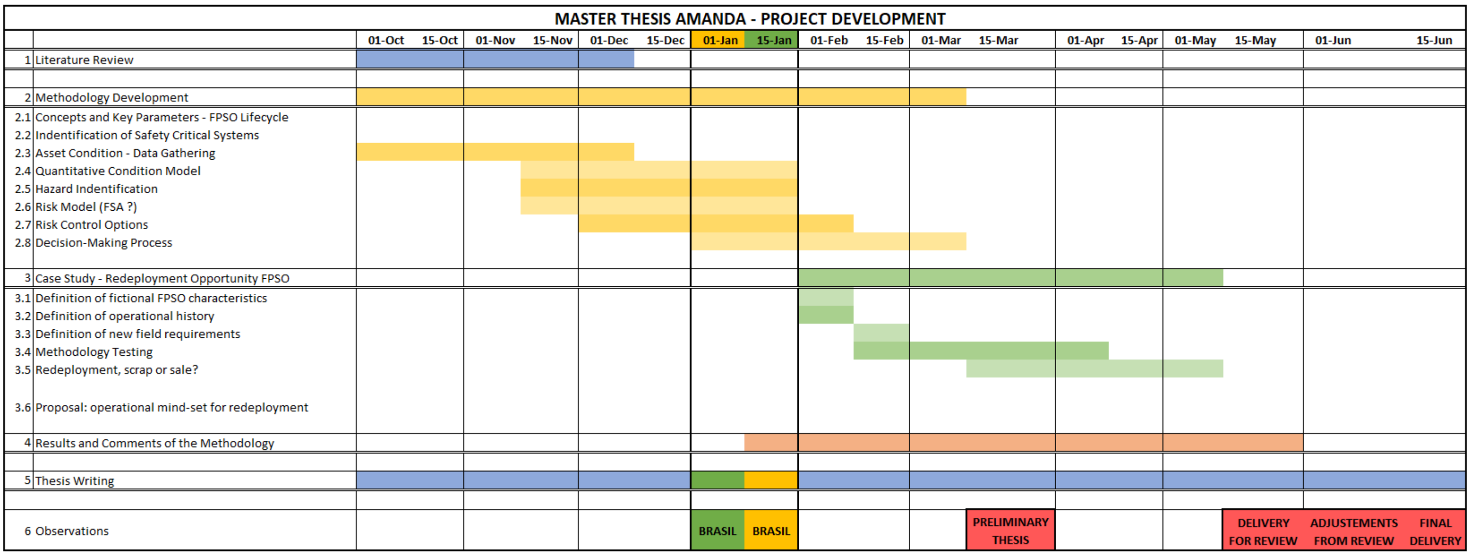
Research Questions

- What is the lifecycle of a FPSO and how does it affect the redeployment process?
- What are the critical systems for a FPSO and why they are so important?
- How do the safety critical systems affect the decommissioning process?
- How can qualitative condition of assets be transformed into quantitative information?
- Is it possible to create a mathematical model to predict remaining useful lifetime of safety critical systems?
- How can risk analysis be used when performing redeployment studies?
- Is it possible to create a risk model for redeployment based on IMO's FSA and is there available information to develop a reliable methodology?
- How are the safety critical systems influencing in redeployment opportunities?
- Can the operation and maintenance strategy be performed in a mindset that focus on extending the asset useful life?

Tasks:

1. Introduction
2. Literature review
3. Methodology development
4. Case Study
5. Discussion of the Results
6. Conclusion

Schedule


MASTER THESIS AMANDA - PROJECT DEVELOPMENT
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5 Thesis Writing
6 Observations
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BRASIL
PRELIMINARY THESIS
DELIVERY FOR REVIEW
ADJUSTEMENTS FROM REVIEW
FINAL DELIVERY

The work scope may prove to be different than initially anticipated. Subject to approval from the supervisor, topics may be added or deleted from the list above or reduce in extent.

The thesis shall be written as a research report, following the template given in Inspera. During preparation of the text, the candidate should make efforts to create a well-arranged and well-written report. To ease the evaluation of the thesis, it is important to cross-reference text, tables and figures. For evaluation of the work a thorough discussion of results is needed. Discussion of research method, validation and generalization of results is also appreciated.

The thesis shall be submitted in electronic version according to standard procedures (.PDF or .ZIP files). Instructions are found on the NTNU website (Inspera) and on Blackboard. In addition to the specified tasks, an A3 poster should be prepared and delivered together with this proposal, and a conference paper will be handled at the end of the research.

After finalizing and delivering the thesis, it must be sent a copy to the supervisor(s).

Deliveries:
Preliminary Thesis (31th March)
Final Thesis + Article (15th June)

Amanda Caroline Rossi
Student – Ship Design
+4746573449
amandacr@stud.ntnu.no

Henrique Murilo Gaspar
Supervisor – Ship Design

Odd Weisæth
CO-Supervisor
Teekay Offshore Production
Tel.
E-mail

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“To reach a port we must set sail –
Sail, not tie at anchor
Sail, not drift.”
— Franklin D. Roosevelt

Abstract

This master thesis proposes a methodology for FPSO life extension project and tests it out in a mock up vessel. The methodology is constructed with concepts from condition status, remaining useful life, risk analysis and life extension work scope. Some marine systems are selected to be analysed: structural systems, offloading system, main power generation system, firefighting system and electronic systems.

Mathematical models are created to predict corrosion effects over time in steel plates, stiffeners and pipes. Rotating equipment are evaluated based on overhauls and replacement strategies provided by suppliers. The proposed framework also calculates man-hours for the scope of work defined, and then costs them based on USD/man-hours or other relevant values.

A FPSO operating in a Brazilian field for 15 years is selected as a case study - it can store 1 MBBLS and process 170.000 BOPD. The life extension project assess the possibility of the unit operating for more 10 years, hence it has a total life of 25 years.

Values for CAPEX and OPEX are defined for the project, and a feasibility economical analysis is performed. The charter rate is calculated for each year in the life extension period and profit margins are selected - both for oil companies and shipowner/operator. The assessment resulted in minimum oil prices required for the project to be profitable for both parts, which can assist decision makers in defining whether to proceed with the project or not.

For the case study, it was seen that the oil price needs to start at USD 43.17 in the first year of life extension period to USD 58.19 at the end. The current value of the brent oil price (May 2020) is just around USD 30.00, hence the project is not yet considered feasible. However, this conclusion can change if the oil prices pick up again.

Abstrakt

Denne masteroppgaven foreslår en metodikk for et FPSO livsforlengelsesprosjekt og tester den ut for et fiktivt fartøy. Metodikken er utviklet basert på at enhetens tekniske tilstand, restverdi, prosjektrisikoer og behov for oppgraderinger for livsforlengelse skal vurderes. Noen marine systemer er valgt for å bli analysert: konstruksjon, avlastningssystem, hovedkraftproduksjonssystem, brannslokkingssystem og elektroniske systemer.

Matematiske modeller er laget for å forutsi korrosjonseffekter over tid i stålplater, avstivere og rør. Roterende utstyr evalueres basert på overhalinger og erstatningsstrategier gitt av leverandører. Det foreslåtte rammeverket beregner også arbeidstimer for definert arbeidsomfang, og prissetter dem deretter basert på USD/arbeidstimer eller andre relevante verdier.

En FPSO som har operert på et brasiliansk felt i 15 år er valgt som en casestudie - den kan lagre 1 million fat olje og behandle 170 000 fat olje per dag. Livsforsikringsprosjektet vurderer muligheten for at enheten skal operere i ytterligere 10 år, og skal dermed oppnå en total levetid på 25 år.

Verdier for CAPEX og OPEX er definert for prosjektet, og en økonomisk analyse for gjennomføringen blir utført. Charterraten beregnes for hvert år i levetidsforlengelsen og gevinstmarginer velges - både for oljeselskaper og reder / operatør. Evalueringen resulterer i antatte minstepriser som kreves for at prosjektet skulle være lønnsomme for begge parter, noe som kan hjelpe beslutningstakere i å definere om de vil fortsette med prosjektet eller ikke.

For casestudien så man at oljeprisen må starte på USD 43.17 i de første årene i det nye prosjektet, og øke til USD 58.19 på slutten. Nåværende verdi av brent-oljeprisen (mai 2020) er omtrent USD 30.00 og prosjektet er foreløpig ikke ansett som gjennomførbart. Denne konklusjonen kan imidlertid endre seg hvis oljeprisene tar seg opp igjen.

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Nomenclature

Acronyms

t_O	Operational Thickness
t_{SV}	Safety Valve Thickness
Δ	Displacement
∇	Volume Displacement
σ_b	Tensile Stress
σ_t	Permissible Stress
C_B	Block Coefficient
L_{OA}	Length Over All
t_D	Design Thickness
AHP	Analytic Hierarchy Process
ALARP	As Low as Reasonable Piratical
ANP	Agência Nacional do Petróleo
API	American Petroleum Institute Gravity
BBLS	Barrels
BCS	Brazilian Continental Shelf
BOPD	Barrels of Oil per Day
c	Corrosion Allowance
CIMM	Centro de Informação Metal-Mecânica
D	Pipe External Diameter
DHGF	Delphi-AHP-Grey Interconnect-Fuzzy Evaluation
e	Strength Ratio
ELT	Estimated Life Time

EPE	Empresa de Pesquisa Energética
ETA	Even Tree Analysis
FMEA	Failure Mode and Effects Analysis
FMECA	Failure Mode, Effects and Criticality Analysis
FPSO	Floating, Production, Storage and Offloading
FSA	Formal Safety Assessment
FTA	Fault Tree Analysis
GOR	Gas Oil Ratio
GRA	Grey Relation Analysis
GRT	Gross Registered Tonnage
HAZOP	Hazard and Operability Study
HFO	Heavy Fuel Oil
IMO	International Maritime Organization
KPI	Key Performance Indicators
LEM	Life Extension Measure
LFO	Light Fuel Oil
MAWT	Minimum Allowable Wall Thickness
NORSOK	Norsk Sokkels Konkuranseposisjon
p	Design Pressure
P_D	Pipe Design Pressure
P_{OP}	Pipe Operating Pressure
P_{SV}	Pressure Safety Valve
PSA	Petroleum Safety Authority
RUL	Remaining Useful Life
SFI	SFI: Skipsteknisk Forskningsinstitutt
SPAR	Sigle Point Anchor Reservoir
USD	US Dollars

Chapter 1

Introduction

This chapter presents the introduction, motivation and research questions considering the topic of the master thesis - life extension of FPSO (Floating, Production, Storage and Offloading) Units. It starts with a brief introduction of the oil and gas industry and the offshore facilities, then presenting the typical life cycle of ships. Life extension and redeployment projects are also discussed, followed by the motivation behind the topic. The section finishes by presenting five research questions to be answered during the development of the thesis and also by illustrating how the thesis is structured.

1.1 The Oil and Gas Industry

The oil and gas industry is the hub responsible for exploration, extraction, production, processing and transporting of oil and gas. In the beginning, the explorations were mainly focused in-land, but soon it was noticed the necessity to develop it further into the oceans. Today, the oil industry is one of the most important stakeholders in the maritime world, responsible for a huge supply chain that involves from oil rigs, exploration and processing units, to shuttle tankers and service offshore units.

It can be mainly divided into three main process: upstream, midstream and downstream. The upstream is related to exploration and production of oil and gas (Maxx Crawford and & Coppinger, 2017), and in the marine industry it is represented by the oil platforms, rigs and FPSOs (Floating, Production, Storage and Offloading) units. The midstream process refers to the transportation of crude oil and gas (Maxx Crawford and & Coppinger, 2017), and is characterized by the shuttle tankers and pipelines. Lastly, the downstream process is the procedure of transforming the crude oil into a finished product, such as fuel and diesel (Maxx Crawford and & Coppinger, 2017).

The economy around the industry has a cyclic behaviour, with many ups and downs. Along the history, the oil price has ranged from as high as USD 160.00 to as low as USD 20.00. Figure 1.1 presents the variation of oil price from 1970 to 2019. One can see a big difference in prices from the period of June 2008 USD 164.22 to January 2019 USD 50.68, meaning that the price reduced more than 3 times its value.

In 2009, it is possible to see the industry trying to recover but again reaching a low oil price that was later increased. In June 2014 the oil price was USD 113.48, reaching USD 36.44 in January 2016. At the end of 2019, the trend seen was that the oil price trying to recover, being at approximately USD 56.20, and many oil fields being tendered for exploration.

Figure 1.1: The oil prices from 1980 to 2000s, from Macrotrends (2019).

By the time of this thesis development (2020), the world is facing a hard pandemic of corona virus that is affecting the way we live. It includes several quarantine rules around the globe that have reduced the demands for oil, as many airplanes are grounded and people are prohibited from circulating. In March 2020, the average price of Brent Crude Oil was less than USD 35.00, and in the end of April 2020 the US oil price went negative for the first time in history.

1.2 The Offshore Facilities

There are many different types of offshore facilities for oil exploration, such as fixed platforms, compliant towers, FPSOs, semi-submersibles, SPAR (Single Point Achor Reservoir) and more (Petrobras, 2019). The scope of this thesis will focus solely on FPSOs.

FPSOs can be divided mainly as ship shaped or mono-column. The mono-column has a cylindrical shaped hull fixed to the seabed with mooring lines, these type of FPSOs can be seen in Figure 1.2. In the top of the unit there is a process deck, where all the equipment necessary to process the oil is located. However, the most common type of FPSO is the ship shaped ones, presented in Figure 1.3.

Those can be new builds or conversions, usually from large tankers. A new-build is a vessel entirely designed to be a FPSO, i.e. the hull is designed from scratch and focused on specific key performance indicators for oil exploration. The conversion ones are normally constructed from tanker hulls, due to the size and configuration specific for this type of vessel.

The hull can suffer minor changes when the storage requirements are met, or can be increased when needed. Adaptations in the structure are necessary in order to meet the requirements for FPSO operation which are slighter stricter than regular merchant tanker. As the mono-column version, the topside is placed at the process deck, where all required equipment's are located.

Figure 1.2: FPSO Mono-Column Piranema (Palmigiani, 2019).

Figure 1.3: FPSO Ship Shaped Knarr (Offshore-Mag, 2020) .

Different needs will emerge when the offshore industry begins to recover - new oil fields will come up and some fields will extend exploration contract. With these recovery trends, the necessity of offshore production facilities shall become once again lucrative. However, building a new offshore exploration structure is not an easy task, and in many cases not even viable as they are highly expensive and time-consuming to construct. Thus, a way out of this problem is extending the design life of units and redeploying it to new fields.

1.3 The FPSO Life Cycle

A FPSO is designed normally to have an operating life ranging from 20-30 years, so to extend its design life, a full overview view of the vessel's life cycle is needed. Figure 1.4 summarizes a typical marine vessel life cycle.

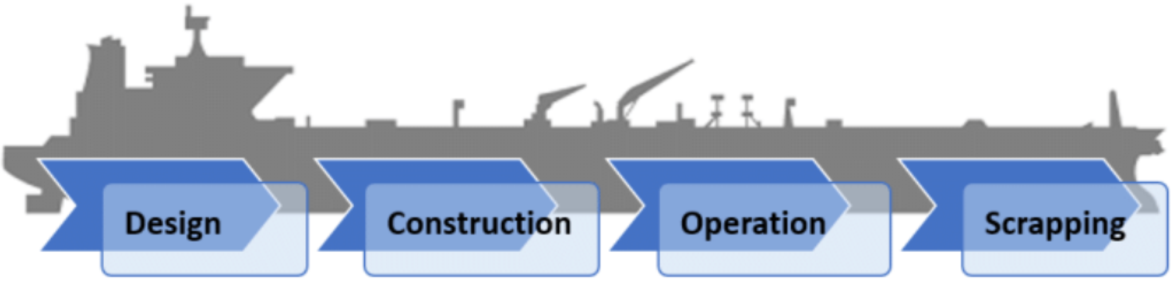


Figure 1.4: A typical Life Cycle of a Ship (Ang et al., 2018).

The first stage on the life cycle of a vessel starts in the design phase, where the idea is developed into a project and documents. Ship design theory itself is a complex iterative process with many phases and definitions that are out of the scope of this work. So, from this time on, when design is referred to, one must consider the detailed design as input to procurement and construction. In this stage, the vessel is completely modelled and how it will look like after construction is already known. The vessel is meeting the international requirements for operation and the KPIs (Key Performance Indicators) defined by the shipowners are already optimized.

Construction is when the project becomes something physical. It is the phase in which the structure is built, the engines are installed and the topside blocks are placed in the process deck. Normally, the procedure is done by a yard, treated as third part contractor for the shipowner. Here, procurement is essential, and a good supply chain management is required in order to plan the construction process and deliver the vessel at the correct time.

The operation phase is the longest phase in the life cycle, and can be a responsibility from the ship operator or shipowner (when the shipowner owns and operates the vessel). Most FPSO units operate for a long time, which can be until the end of the life cycle of the field, but not necessarily the end of their own life cycle. Thus, after the operation comes another crucial phase: decommissioning. The decommissioning process is an important business decision and is the main focus of this master thesis. Therefore, it is important that the concept is clearly understood.

> "Decommissioning (also called abandonment) is the process by which the owner operator of an offshore oil or gas installation will plan, gain approval for, and implement the removal, disposal, or reuse of an installation when it is no longer needed for its current purpose" (Speight, 2015; apud Jahn et al., 1998; Ekins et al.,2006).

Deciding whether an older vessel is suitable for continued operation is a difficult process. Many different aspects must be evaluated, like the structural condition, capacity, and operation expenses. Converted FPSOs can be an even more challenging issue, because one must consider the life of the previous vessel and all the changes made to turn it into an oil exploration asset.

1.4 Life Extension and Redeployment

The decision of extending the life of a unit is based in technical and economic aspects - it is always a balance on "how much money is needed to extend the operating life" to "how much money will this bring to the company". Thus, the concept is simple: the money spent on "fixing" the unit to operate longer and the operation costs should always be lower than how much money the company will make. At first, the concept might seem simple, but it requires a full understanding of the unit's condition to decide whether it is a fit or not for extended operation.

If the company decides to extend the life and redeploy a unit, some design process will probably need to be redone. There will be upgrades needed in structure and layout, which shall require new analysis. The topside part of the FPSO will need to be revised and possible new blocks are going to be required. Procurement will be necessary, and updates and repairs shall be performed at the unit before it is back on operation.

Indeed, there are many benefits when redeploying a unit to a new field, however, as one can probably feel so far, this is not an easy task nor is a straight forward decision. The decommissioning process is influenced by different areas of an oil and gas company, such as the maintenance, operation and administration. Decisions made in each of those areas have a significant impact in the future of the units, as for example postponing maintenance of a specific system that might become extremely expensive at the life extension phase.

The objective of this thesis is to propose a procedure in which life extension of FPSO units can be assessed in a efficient and fast manner, considering the "As Is" status of the unit and what shall be done for the future so that the unit can operate safely for longer time - i.e. a procedure linking the present condition to future operations. Using the methodology, one shall be able to have enough information that can support the decision of whether the unit is suitable for life extension or not.

1.5 Industrial Motivation

The thesis idea emerged during an internship at Altera Infrastructure, at the Early Phase and Innovation department, and it was developed in cooperation with the company. In Altera Infrastructure, the supervisor was Odd Weisæth, while in NTNU it was professor Henrique Gaspar.

Redeployment of FPSOs are an interesting solution for both shipowners and oil companies when compared to new build vessels. Building a new ship is a time consuming and extremely expensive task, and considering the behaviour of the oil price, also a risk investment. Therefore, having a unit that requires less effort to be ready for operation, means starting production earlier - in this way, it is a win-win for both side.

The challenge sits on the fact that it is not a straight forward process, and requires a lot of study to prove the unit is safe for operating longer. Hence, this master thesis shall assess the possibility of creating a methodology to assist on life extension analysis - that is considering that the FPSO will operate for longer at the same field.

1.6 Thesis Objective and Research Questions

The thesis main objective is to develop a process to assist in decision-making process, hence different models are developed that can be later used to conclude whether it is feasible to extend the operation of a FPSO for longer. The methodology behaves as a learning process during its entire development. Initially, what life extension means must be studied and defined, so one can assess all the work that should be carried out. There are typically four different categories associated with extending the operational life of an asset: life extension, compliance, upgrades and renewal.

However, a FPSO is a gigantic structure with numerous systems, subsystems and equipment's, therefore it is necessary to shorten the amount studied. It is common to have status at the equipment level, but for a fast and efficient approach, it is necessary to understand the condition of the systems. The methodology shall identify some specific systems for life extension and propose a procedure to gather the information on them.

With the systems identified, it is necessary to understand how they impact the asset performance and life extension scope of work. There are different risks associated with each system, from changes in regulations to complete system failures, thus, it is vital that the risks associated with life extension are fully understood.

The same system can have different risk categories, so it is important that a "general" risk picture is defined. Risk mitigation also influences the life extension strategy - one must understand what is the actual cost of doing something regarding a problem now, or if it is better to wait until upgrades start to be done.

Literature is available regarding calculating the remaining useful life of equipment's, and it is much more complex than simply calculating the design life of the equipment minus the time in operation. The way the equipment was maintained, and its actual condition are the factors that will drive most of this estimation. This thesis shall investigated if it is possible to create a mathematical model to predict the remaining useful life for some of the systems in the FPSO. Quantitative measurements about the unit are much more effective and easy to cost than a qualitative one. Thus, a big challenge on the methodology is understanding how to measure and quantify most of the information needed, as a major part of it will be found simply as a condition status.

A detailed cost model is out of the scope of this thesis, but some high-level studies and analysis shall be performed so that guidelines on decision-making can be created. This is done by using the concepts related to CAPEX and OPEX, which are the capital expenditure and operational expenses, respectively. At the end, the methodology shall be tested out in a mock-up FPSO, in order to check its applicability. Work packs shall be created gathering all the life extension scope of work and then a feasibility analysis is carried out to decide upon what range of oil price is the project profitable in comparison to selling the unit for scrap.

The research questions to be answered during the development of this thesis are listed below:

- Is it possible to create a methodology to assess life extension of FPSO units?
- What are the important factors to be included in this methodology considering the decommissioning phase of the unit?
- How can one organize the required information available into the methodology?
- What are the risks associated with life extension and how can they be mitigated?
- How the developed methodology can be validated, extended and used to in the decision-making process of life extension?

1.7 Thesis Structure

This master thesis is divided into 6 chapters:

1. Introduction: presents an introduction about the oil and gas industry, FPSOs and their life cycle, life extension and redeployment, as well as the thesis objective and research questions.
2. Literature Review: this chapter describes all the relevant literature for the master thesis. It includes concepts of marine system engineer, project and product life cycle, risk analysis, life prediction models and decision making for redeployment and life extension projects.
3. The FPSO Life Extension Methodology: chapter 3 is responsible for describing fully the proposed methodology, which is dived into 7 phases. It defines what are the life extension requirements, how to define the asset condition and life extension scope. Quantitative models are created to predict useful life of systems and time between overhauls and replacements. Then a risk analysis and risk mitigation procedure is studied, and the methodology ends by defining work packs, with a cost estimation followed by an economical feasibility analysis
4. FPSO and its Marine System - A Mock Up based on Real Life Scenario: this chapter describes a mock-up FPSO and the necessary systems to test out the methodology developed.
5. Case Study - Life Extension Assessment of the FPSO: the methodology testing in the defined FPSO are presented in this chapter, as well as the analysis of results.
6. Concluding Remarks and suggestion for Further Work: the last chapter of the thesis ends with the conclusions and suggestions for future work.
7. Appendices: this section presents all the information in appendix for the master thesis development.
   Appendix A - Methodology Development
   Appendix B - FPSO Description
   Appendix C - Case Study
   Appendix D - Thesis Article

Chapter 2

Literature Review

This chapter presents the literature available on life extension of FPSO units and the topics to be addressed during the methodology development. It starts by giving a general overview of FPSOs, followed by a section with concepts related to systems engineering and the maritime world. Then, the life cycle of a FPSO and the redeployment projects are studied, presenting a proposed life cycle for the project itself. A section presenting the specifics of the decommissioning process is delineated, introducing redeployment and life extension projects. Risk analysis and risk management in shipping activities are also covered, characterizing the concepts related to IMO's FSA and technical risk management process from NASA. The chapter finishes by giving an overview of life prediction models available to determine the remaining useful life of systems and how the decision making process for life extension has been developed in different studies, linking studies with methodologies as the one to be proposed by the master thesis.

2.1 Marine Systems Engineering

A marine vessel is physical structure composed by different systems and elements, that when connected allow for the execution of a mission. Kapurch (2010) defines that "a system is a collection of different elements that together produce results not obtained by the elements alone". In a ship, one can see different systems as for instance the hull, propulsion system, control systems and storage areas. Separately, these systems have their own mission and performance, but together they generate the overall function of the vessel: safely transporting products from A to B. Without each one of them working together, the vessel would not float, store cargo nor navigate, thus its mission would not be achieved.

Although NASA's Handbook of Systems Engineering (Kapurch, 2010) is related to the Aerospace Engineering, the concepts can be extend to Marine Engineering due to the similarities of the products - both ships and aerospace crafts are huge unique designs, that require a specialized team in order to build the final outcome (Pedreira, 2018).

Systems engineering thinks in the whole procedure instead of the local influence of each element. One can define it as logical way of thinking while assessing the big picture (Kapurch, 2010). According to the NASA System's Engineering Handbook (Kapurch, 2010), when applying system techniques, one can achieve a balance between organization and technical interactions at complex systems. It is vital that the project manager has the skills of systems engineering and project control, summarized by Figure 2.1. To have an effective and productive project management system, it is necessary to have the knowledge from both areas, where project control gives direction into cost and schedule, and system thinking provides inputs to the technical part (Kapurch, 2010).

The interaction between these two set of skills gives what is necessary when assessing if a unit is suitable for life extension. For instance, the planning considers understanding what, how and when the scope of work to extend operation life shall be done, while risk management evaluates the risks related to the life extension project. Data management is crucial for this type of project, because data is everything that will be analysed. It ranges from documents to condition status in equipment and systems, thus it is vital that data is created, collected and stored.

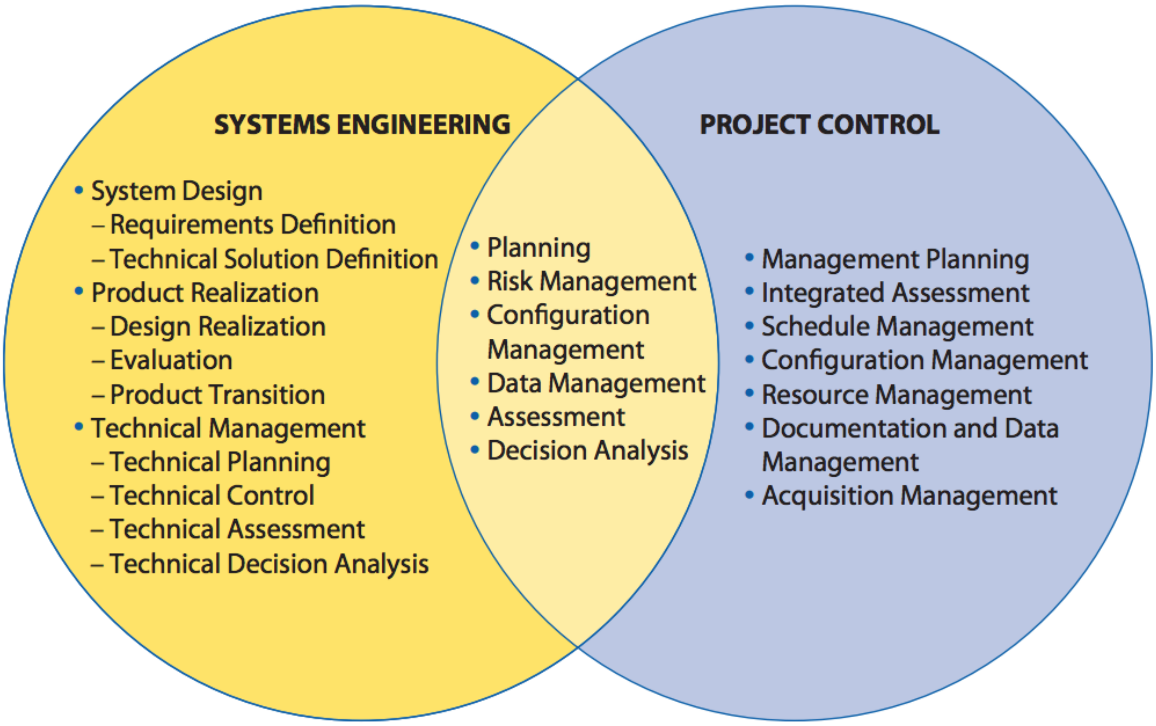


Figure 2.1: Systems engineering and project control at project management (Kapurch, 2010).

Ships are, nevertheless, complex systems. According to Gaspar et al. (2012) "the idea of a ship as a system (...) is so well established in the design field that, from Evans (1959) until nowadays, it seems impossible to discuss the design problem without discussions about a system". The complexity of a system is extremely attached on how one describes the system, so as more subsystems are needed, the more complex it is (Gaspar et al., 2012; Simon, 1991; Kolmogorov, 1983). A FPSO, for instance, is a complex system composed by many subsystems and components.

2.2 Floating, Production, Storage and Offloading - FPSOs

Floating, Production, Storage and Offloading units, FPSOs, are large marine systems that can produce and store oil and gas. From the configurations available: ship shaped and mono-column - this thesis focus only in ship shaped structures, but the concepts can be extended to mono-columns as well.

According to Paik & Thayamballi (2007), ship shaped offshore units have proven to be a great solution for oil exploration in deep water: reliable and cost-effective. They allow for the exploration of oil fields that were impossible to explore before - further away from shore and with increased water depth.

When compared to other types of offshore units, FPSOs have different benefits, such as bigger work area, more available deck load, better structural strength and high storage capacity (Paik & Thayamballi, 2007). The units can also be derived from conversion and are able to be re-utilised. Paik & Thayamballi (2007) also states that FPSOs have lower building/capital cost and shorter lead time when compared to other units.

The mission of a FPSO is to be an offshore vessel, seaworthy and capable of continuously producing oil during the entire field or vessel operational life, while giving safe operation conditions to its crew and the environment (Lamb et al., 2003). As offshore exploration developed further into the oceans, the need for units that could handle deeper seas emerged and FPSOs became a great option. However, the vessel response in harsh weather conditions is a critical factor, specially considering green water, sloshing and slamming (Paik & Thayamballi, 2007).

The vessel's motion play an important role in design of mooring and riser systems. Riser systems are mostly flexible, and the mooring type vary from turret and spread mooring, to articulated tower and soft yoke systems (Paik & Thayamballi, 2007). Specifically for benign waters, the assets can have a spread mooring configuration and rigid risers.

FPSOs are either new builds or conversion from oil tankers, and the challenge in design remains at the structural part. A 100-year return period shall be used to assess onsite structural strength during design stage, while inspection and maintenance optimization shall be performed in operation (Paik & Thayamballi, 2007).

Although the visual similarity, and some even being an oil tanker before becoming a FPSO, there are huge differences between oil tankers and FPSOs that must be understood. Figure 2.2 summarizes the differences between these two vessels.

Trading tankers	Ship-shaped offshore units
Design condition: North Atlantic wave environment	Design condition: Site- and tow-route-specific environments
20- to 25-year return period	100-year return period
Predominantly wave actions	Currents as well as wind and wave actions
Limited number of loading/offloading cycles; loading occurs in sheltered situations	More frequent loading/offloading cycles; loading occurs with relatively more environmental effects present
Limited number of loading conditions	More numbers and variety of loading conditions
At open sea for about 70 percent of the time	Offshore for 100 percent of the time
Weather in any direction; rough weather avoidance possible	Highly directional weather and weathervaning; rough weather avoidance not possible once on site
Regular dry-docking every 5 years	Continuous operation usually without dry-docking
Without topsides	With topsides and associated interaction effects between hull and topsides

Figure 2.2: The differences between tankers and FPSO's (Paik & Thayamballi, 2007).

When deciding on a new build or conversion, different advantages and disadvantages will arise. Paik & Thayamballi (2007) apud Parker (1999) presented some of the advantages of a new build:

- Design and strength criterion's can be achieved easily;

- Risk can be easily contained, regarding technical, commercial and environmental aspects;
- The survivability in harsh weather can be be achieved easily;
- Possibility to maximize resale and residual values;
- Opportunities to reuse the asset;

Considering the conversions, Paik & Thayamballi (2007) apud Parker (1999) states that the advantages are:

- Reduced capital costs;
- Less extensive and faster design and construction;
- Availability of local to construct is higher;
- Possibility of less overall project supervision requirements

Different aspects are driving the decision between new build or conversion, and each case must be evaluated on its own way. However, the field life is an important requirement that must be taken into consideration. Usually, for continuous operation of more than 20 years, new builds are the desired option, while for operating life of around 5-10, or even 15 years, conversions might be viable (Paik & Thayamballi, 2007).

There are mainly two different sections on a FPSO - the hull and the topside. The hull is a typical displacement hull, very large so that it can store as much cargo as possible. The topside is the process deck where all the equipment necessary to production is placed. The hull of a FPSO is usually built by regular shipyards, improving the strength at areas that are needed. The topside, however, requires some more specialized contractor, and later are integrated to the hull at the shipyard (Paik & Thayamballi, 2007).

Offshore structures, and specially FPSOs, are mainly floating factories that gathers basically marine system and process systems. A marine system are those related to the marine mission of the unit, that is to be able to float, sustain the hydrodynamics and hydrostatics loads, and to keep its position while maintaining the correct stability.

The process (or topside) systems are the ones specific for oil processing and production. At first, it might seem that the definition is clear and that the system's boundaries are easy to define, but it is actually the other way around. The same component can be used both for marine and process systems, for example the engines. They are located inside the hull, but provide energy to all the systems onboard.

The oil is extracted and then processed by the topside systems, but it must be stored somewhere. Hence, it is transported to the cargo tanks, which in principal are a marine system as they affect directly the vessel's stability and structural strength.

2.3 Life Extension Project and FPSO Life Cycle

There are different aspects when considering life cycle, as one can have it for product and project. The project life cycle starts with the definition of a problem to be solved, considers all the phases of its development, until its closeout (Kapurch, 2010). According to Kapurch (2010), among the stages of project life cycle, there are:

- Pre-Phase A: Concept Studies to identify feasible solutions

- Phase A: Concept and Technology Development
- Phase B: Preliminary Design and Technology Completion
- Phase C: Final Design and Fabrication
- Phase D: System Assembly, Integration and Test
- Phase E: Operations and Maintenance
- Phase F: Close-out

With the stages well characterized and established, it is necessary to define a program to guide the project execution, which shall meet cost effectively the technical requirements and organizational objectives (Kapurch, 2010). In this program, some key decision points must be set, so that reviews and analysis are done to decide whether it is suitable to continue to the next phases. Figure 2.3 summarizes well the project phases and decision points from NASA Systems Engineering Handbook:

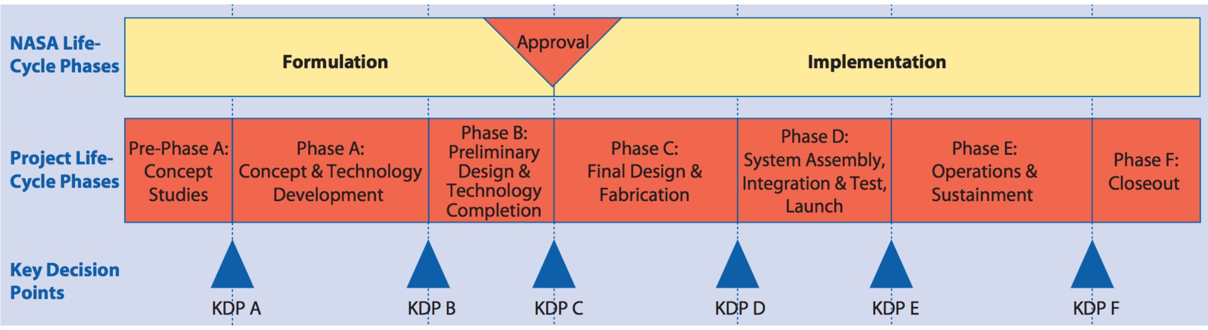


Figure 2.3: NASA Project Life Cycle (Kapurch, 2010).

This master thesis divides the projects to extend the FPSO life in two ways: life extension project and redeployment project. The differences between them both lies mostly in the oil field location - for life extension project the unit shall remain at the same field, while when being redeployed the asset is moved to another location. Both projects are in their essences a new project to the company, thus have a similar life cycle to what is defined in the NASA handbook presented above. The degree of detail from the project gets higher from phase to phase during its development.

Expanding the definitions from the stages in project development, the pre-phase of a life extension / redeployment project shall assess the condition of the unit and possibilities to be redeployed or to have its operational life extended. Then, phase A shall consider the field itself, defining if the unit is a fit and performing some high-level cost estimations based on inspections and condition status. Phase B must go deeper into the scope of work, determining a more accurate work scope to improve the asset condition and a more accurate cost estimation.

If the unit is decided as suitable, the FEED (Front-End Engineering Design) engineering parts takes place and is described as phase C, where the detailed work scope in the asset is established and the cost estimated is precise. In redeployment projects, this phase is followed by normally taking the unit to the yard - in case going to the yard is necessary to perform the required work to have an working asset - then moving it to its new location. Phase E refers to the operation of the FPSO, including the maintenance and day-to-day operation. Lastly, the project is closed out, and pending on the history of long time operation pattern before and that the asset has already operated longer than initially designed for, it would probably mean scrapping the unit. Figure 2.4 presents this typical FPSO redeployment project formulation based on what was defined before by Kapurch (2010), also illustrating some key decision points. After each phase, the management team needs to evaluate whether the results are in accordance with business strategies and technical aspects before going further into the project development.

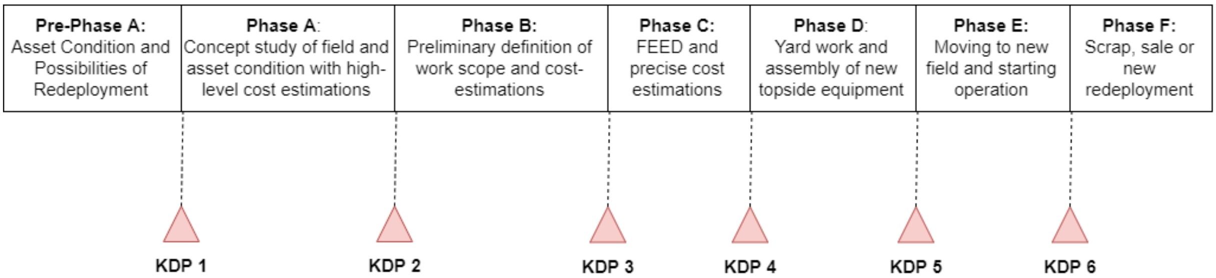


Figure 2.4: Redeployment Project Life Cycle based on Figure 2.3 (Kapurch, 2010).

Another representation of engineering project life cycle is presented by Roseke (2015). Here, the author divides the project life cycle in 6 phases: concept, feasibility, preliminary engineering, detailed design, execution and testing and commissioning. A general overview of the phases is presented on Figure 2.5.

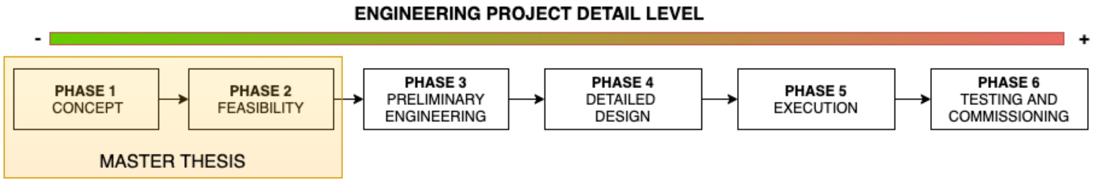


Figure 2.5: A typical Life Extension Project Life Cycle based on Roseke (2015).

According to Roseke (2015), concept is the phase responsible for finding opportunities and starting to develop a concept that will be later developed further. In a life extension project, this stage would be responsible for initiating the analysis of whether the unit is suitable for life extension or not, based on expert opinion on systems condition. This phase is followed by the feasibility study, where some cost estimations start to be made and more analysis can be performed into the project. Roseke (2015) states that feasibility studies usually estimate the costs to a level that can give sufficient confidence for the business manager to decide whether to proceed with the project or not.

The life cycle follows with preliminary engineering, where calculations can be done and engineering software's can be used. Detailed design is the next phase, and similarly to the previous one, more complex engineering calculations and procedures take part. Phase 5 is execution where the work planned before is implemented in order to proceed to phase 6 - once properly constructed the engineering project can be tested out and commissioned (Roseke, 2015).

The life cycle of the life extension / redeployment full project, usually takes around one to two years, but in parallel and running for the entire asset operational life, is the FPSO life cycle. Any product life cycle relies in three aspects: business, budget and technical - all these three factors must be in balance and have equal weights in the procedures for the sake of system's integrity (Haskins, 2006). A typical life cycle of a FPSO unit is presented in Figure 2.6.

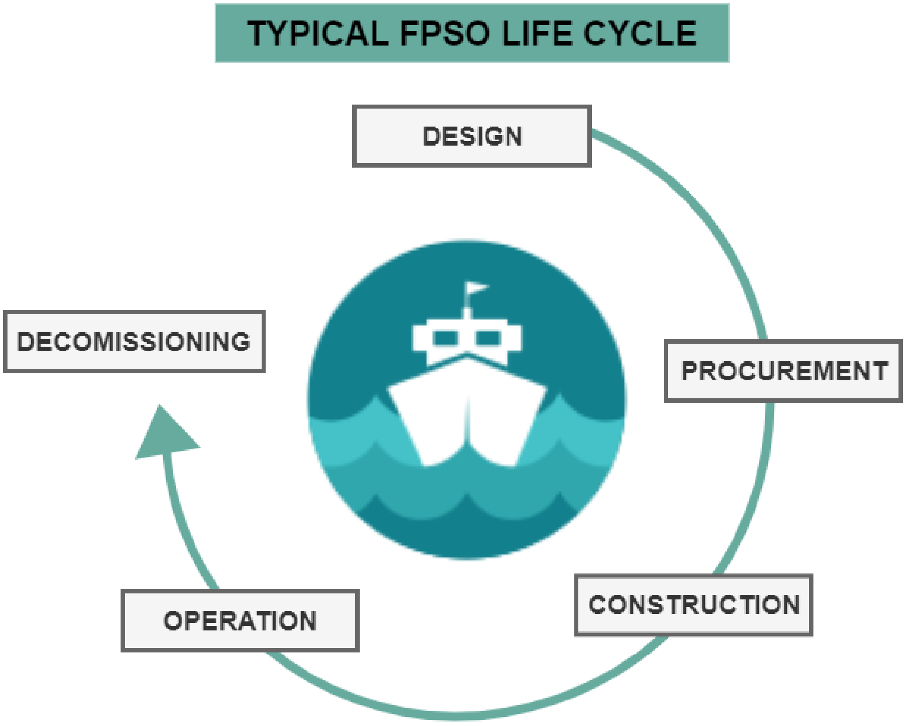


Figure 2.6: Typical FPSO Life Cycle.

The life cycle of a product starts in the design process, where an idea to meet a determined set of requirements is projected. Ship design itself can be divided into different stages - concept, preliminary, contract and detailed design (Lamb et al., 2003), but with the objective to study the FPSO life cycle, the last phase shall be considered: detailed design. The final phase of design gathers the necessary information for the construction of the vessel. At this stage, all the necessary engineering calculations were made and design decisions were taken. Here, the level of detailing is high enough so that the unit can be built at a yard, and the final cost of the vessel can be precisely determined (Lamb et al., 2003).

Subsequently, the procurement phase starts and it is when all the suppliers are selected. Procurement can have different meanings and applications during the life cycle, as there is procurement from ship building to ship operation. This stage is followed by construction, where the physical building process will take place at a shipyard. In this stage, the systems must be integrated and tested, stability and inclining tests are performed and lastly the unit is proved in the open seas with sea trials. With the unit approved and delivered to the ship owner, it is transported to the field location and its operation can begin (Lamb et al., 2003).

The decommissioning stage considers defining whether the unit will be life extended/redeployed, scrapped or sold. This is an important business decision and surrounded by a different set of requirements, that range from environment considerations when scrapping the unit to the design requirements for the unit to be redeployed (Dinu & Ilie, 2015).

Besides the life cycle of the vessel, it is imperative to also understand the costs associated with the vessel. Barringer et al. (1995) presents a generic definition of life cycle costs:

> "Life cycle costs are summations of cost estimates from inception to disposal for both equipment and projects as determined by an analytical study and estimate of total costs experienced during their life." (Barringer et al., 1995)

The author also states that life cycle costs are important to assist the design and engineer teams on the selection of what equipment should be used - this way one can focus on the entire product cost instead of only the purchase price. In many approaches, only the procurement cost is the main criteria for choosing equipment and systems but they do not tell the full story (Barringer et al., 1995). Barringer et al. (1995) defines that the life cycle costs can be used to perform affordability studies, find trade-offs in design, perform an analysis in repair level, to influence sales strategies from suppliers, as well as to influence warranty and repair costs.

According to Dinu & Ilie (2015), the costs during the ship life cycle can be divided into the initial cost, maintenance and operation costs, failure costs, repair and recycling costs. The initial costs are the prices associated to the project development and vessel construction, followed by the maintenance costs. The operation costs gathers the prices for the parameters influencing the day-to-day operation of the unit, such as crew wages and fuel. The failure costs are related to fatalities, injures, salvage and environment prices due to accidents, than can range from operational accidents hurting the crew to oil leakage. Repair costs are the prices in services to extend the design life of the unit, and recycling is the category associated with scrapping the vessel (Dinu & Ilie, 2015).

2.4 The Decommissioning Process

The decommissioning process was briefly presented in section 2.3, but as this is the stage in the unit's life cycle which is the main topic of the thesis, special attention must be given to its concepts. There are basically three main decisions to be made in the decommissioning process: life extension / redeployment, scrap or sale as available on Figure 2.7 - all with their own requirements, benefits and challenges.

One must consider that there are two different decommissioning processes involved in the process - the asset and the field decommissioning. The field decommissioning must deal with all the sub-sea facilities involved into the exploration. A planning must be created to the wells and pipelines as well, and different regulations must be followed when the decommissioning process is to take place.

The process of leaving an oil field is rather complex - the operators cannot simple transport their vessel to another location nor leave the unit standing still. A decommissioning plan must be created that involves the disposal of the unit and all of its components, as well as an impact assessment to the environment (NorskPetroleum, 2019).

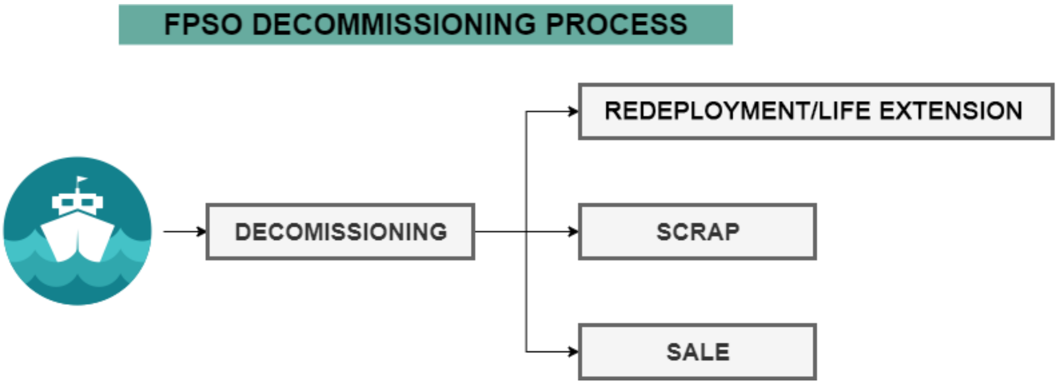


Figure 2.7: FPSO Decommissioning Process.

The scrap process refers to recycling the unit, and it is regulated by the IMO since 2009, from the convention “Safe and Environmentally Sound Recycling of Ships” held in Hong Kong. The objective of the convention was to create guidelines to ensure that the recycling process does not threaten human health or environmental safety. The ship is sold to a recycling yard that makes profit by selling the steel. However, many vessels carry hazardous materials that require a proper scrapping plan, which makes it a dangerous process when not performed correctly (IMO, 2019).

The second possibility in asset decommissioning is selling the unit. The clients can range from shipowners and operators, to shipping companies that have some sort of plan for the vessel. The condition of the asset must be enough so it becomes a lucrative project for the buyer. Different aspects influence the buying of a vessel that rely not only in its integrity status, but also in its documentation and bureaucratic issues, such as inspections and certifications.

The final option for a FPSO is having its life extended - being moved to a new oil field or extending operation in the original field. As stated before, this thesis treats these two possibilities as separated projects: life extension project and redeployment project. A redeployment project happens when the original field stops production from reasons that vary from reaching its operational life to problems considering environmental regulations and funding, but the FPSO can still operate for longer in another location. The other way around can also happen with the life extension projects, as the field can have an operational life longer than anticipated and the FPSO might be required to extend its operation as well.

When assessing if the units is suitable for life extension / redeployment, the owners must understand the real condition of the unit - which systems are good and bad, how extensive is the scope work needed and how many obsolete equipment’s need to be replaced. Rarely, a FPSO is designed and built to be used in multiple fields, for different reasons that include funds and host-country needs (Parker, 1999). Thus, in redeployment projects not only the integrity of the unit has to be defined and studied, but also the requirements of the new oil fields. For example if there is a redeployment opportunity into the North Sea for a unit designed to benign waters, there might be a chance this unit is not an actual fit. For this reason, this thesis will develop the methodology to assess only life extension projects, hence not considering any field specific changes.

2.5 Risk Analysis and Risk Management in Marine Engineering

Risk analysis and risk management are the procedure’s of identifying hazards and risks associated with a determined process, and understanding how to reduce and control these elements. In the maritime world, it is mostly associated with ship design, construction and operation. It is usually seen as a reactive process, where one studies accidents that have happened in order to comprehend the risks and causes associated with it, so that new accidents can be prevented (IMO, 2019). The Formal Safety Assessment, FSA, is a procedure proposed by the IMO (International Maritime Organization), described as:

> “A rational and systematic process for assessing the risk associated with shipping activity and for evaluating the costs and benefits of IMO’s options for reducing theses risks” (IMO, 2019).

Its objective is mainly to compare existing guidelines, to improve rules and to create new regulations so that maritime safety can be enhanced. Identifying benefits, such as reduction of loss of life and lower pollution impact, considering the costs associated with it allows the IMO to propose new regulations that can benefit the industry. The FSA is divided into 5 steps, plus a initial step known as problem definition (IMO, 2019):

- Step 0 - Problem Definition

- Step 1 - Hazard Identification
- Step 2 - Risk Analysis
- Step 3 - Risk Control Options
- Step 4 - Cost Benefit Assessment
- Step 5 - Recommendations for Decision Making

The Step 0 can be defined as a screening approach, where the type of ship to be studied must be characterized into a generic one, i.e. defining a range of GRT (Gross Registered Tonnage), and identifying a suitable database to find information from, such as flag state and accident investigation boards (IMO, 2019). It is fundamental to also classify the type of accident being studied in order to account for likelihoods when creating a quantitative model. Also, risk acceptance criterion's are identified for understanding the risk associated with the operation and what possible control measures could be performed (IMO, 2019). To perform a FSA, it is imperative to have expert judgment - i.e people with the necessary knowledge, such as operators, masters, and chief engineers.

With the problem characterized at hand, the methodology proceeds into its 5 phases. In Step 1, it starts with a hazard identification done by available techniques in risk analysis, like FMECA (Failure Mode, Effects and Criticality Analysis), and HAZOP (Hazard and Operability Study), using the information available in databases and expert judgements (IMO, 2019). The result of this phase is to describe the most relevant hazards associated with that ship type and later rank them to name which should be prioritized or discarded (IMO, 2019).

The FSA proceeds in Step 2 with the risk analysis, which is the development of a risk model to investigate the causes, initiating events and consequences of an accident (IMO, 2019). Once again, available techniques in risk analysis such as FTA (Fault Tree Analysis) and ETA (Event Tree Analysis) , can be used to establish which areas are the high risked ones and should be controlled. The decision upon which technique to be used depends on the quality of available information (IMO, 2019).

Step 3 consists of using the outputs of the previous phases to propose risk control options. The same risk model can be used, once the control points are performed to some specific parts of it (IMO, 2019). While suggesting ways to reduce risk, the analysis shall also present how much of it is reduced when compared to the previous risk model. Then, Stage 4 is carried out, when those control options are evaluated in a cost manner. The economical impact of performing the suggested is defined in order to identify when those are cost beneficial. Step 5 finishes by proposing a recommendation for decision making based on the outputs of all the five previous phases (IMO, 2019).

Risk analysis is also an important factor in project management, and prescribed as Technical Risk Management Process by Kapurch (2010), in the NASA Systems Engineering Handbook. Kapurch (2010) states that risk is a combination of the probability of an undesired event happening during the project along with its consequence, severity and impact. The author defines that:

> “Technical risk management is an organized, systematic risk-informed decision making discipline that proactively identifies, analyzes, plans, track, controls, communicates, documents and manages risk to increase the likelihood of achieving project goals” (Kapurch, 2010).

Project management involves different strategies regarding project risk, such as transferring performance risk, eliminating risk, reducing the likelihood of hazardous events and uncertainties, reducing the negative outcomes of risk and so on. Technical risk management assesses the technical risks related to the project, but these always have an impact in cost and business decisions (Kapurch, 2010). Figure 2.8 presents an overview of the technical risk management process proposed by NASA.

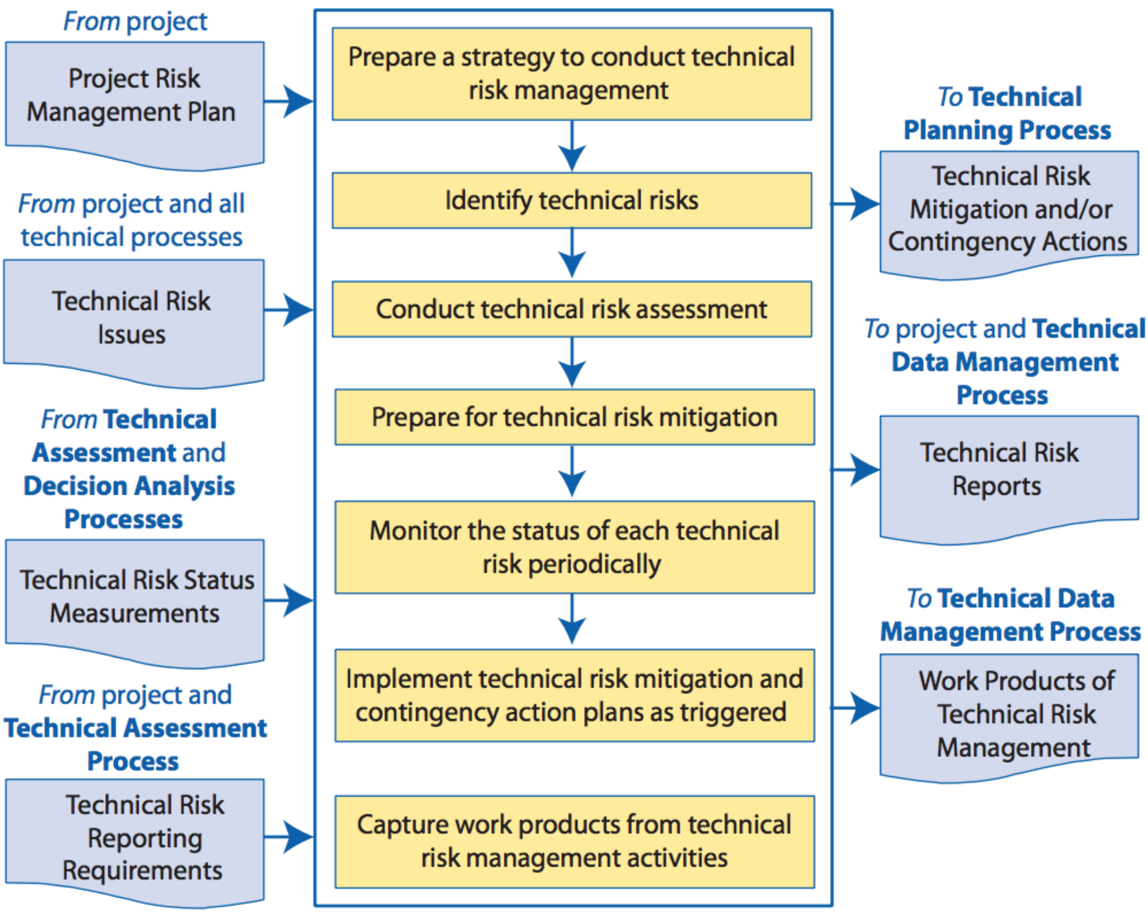


Figure 2.8: Technical Risk Management Process (Kapurch, 2010).

It is divided mainly into three phases - inputs, process activities and outputs. The inputs consists of determining all the key parameters that will affect the risk management plan, such as plans and policies, technical inputs and relevant data and experience to perform an analysis of possible mitigation actions (Kapurch, 2010).

The process activities are responsible for identifying and assessing risks associated with the mitigation's proposed. One must perform an assessment and risk ranking of the solutions, while iterating it with the entire project life cycle. With the process activities performed, the outcomes should be a plan to address a specific risk, as well as technical factors related to the mitigation's defined. If the process is not yet satisfactory, the process should be redone until good results are achieved (Kapurch, 2010).

Risk analysis is crucial in decommissioning, in a life cycle perspective and in a project management view. The risk associated with it must be established, characterized, and mitigated, so one can have a successful life extension /r edeployment project of a FPSO unit, in both safety and economical aspects.

The FMEA (Failure Mode and Effects Analysis) is the chosen technique for the risk analysis to be performed in this thesis and it consists of classifying the possible failure modes and its effects in relation to a specific systems. There are different templates available that can be adapted for each unique risk analysis. For this thesis, the FMEA analysis is performed for the systems identified and is divided into 4 main groups. The first group consists of characterizing the system and its condition - this is done by describing the system function and its status (later referred to as life extension assessment). Then, a failure description is carried out that identifies the failure cause/mechanism, the failure mode and a detection method to it. The 3rd group of assessment are the failure effects, where one can identify the local and global effects, as well as define a consequence. Lastly, a risk ranking is done by assigning values of likelihood and consequences, and then multiplying them to calculate the risk.

2.6 Life Prediction Models

When analysing the condition status of a FPSO, different types of information are available. However, most of those are merely qualitative data, that can vary from a system being obsolete to a condition being unclear or average. For example if a control system is assigned as obsolete and the regulations states that to get approved a determined type is needed, in consequence it is easy to conclude that the entire control system will need replacement, making it obvious to get a cost into that. Contrarily, if a different system gets an unclear or average condition, it is not straight forward to understand what is the extend of the work to be done in life extension, to such a degree that makes it difficult to get a quote for the activities needed.

Assessing the cost and extension of the work required in the life extension project would be easier if it was possible to identify a quantitative value to the systems. Thereupon, knowing how much remaining useful life, RUL, is available for the critical systems is interesting to understand what should be done to extend the life fulfilling the requirements in the project. This would allow for a more accurate cost estimation, creating a more direct decision making process when analysing if a unit is suitable for having its operational life extended or not.

Okoh et al. (2014) defined RUL as how much time is available for a system to operate before reaching failure. There are different techniques to predict RUL but according to Okoh et al. (2014), those are mainly model-based, analytical-based, knowledge-based or by a simulation hybrid-method, which are presented in Figure 2.9. The analytical based consists of physical prediction of failure modes, while model-based and knowledge-based gathers concepts from statistic, computational intelligence and experience. The Hybrid-based uses different approaches to have a more accurate predictions (Okoh et al., 2014).

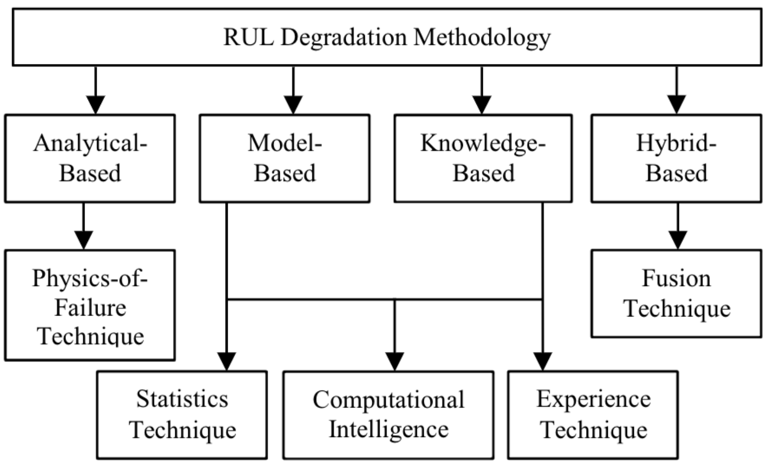


Figure 2.9: RUL Techniques (Okoh et al., 2014).

To define the system's RUL, it is necessary to understand and identify what are the failure mechanisms associate with it. Some of the common types of degradation mechanisms are wear, corrosion, fracture and deformation (Okoh et al., 2014). A FPSO can be roughly defined as a floating factory, thus its process and marine systems have different failure modes. Traditionally, not many systems in the FPSO have their RUL predicted, thus the methodology to be developed shall study the possibility to extend this concept for a life extension project.

2.7 Available Literature in Decision Making Process for Redeployment and FPSO Life Extension Projects

For life extension porpoises, the decision making process is basically focused on whether the unit is suitable for life extension or not. Normally, this concerns maintenance and repair prior to extending the operational life of the unit - it is always a trade off between doing it when going to yard (if applicable) or carrying it out while in regular operation. Several authors have performed researches about life extension of ageing offshore platforms.

According to Tan et al. (2016), the life extension decision making is a serious and complex problem, as uncertainty among maintenance data and possible risks is extensively present. In most cases, the decision process is based in a balance between risk and cost (Tan et al., 2016).

The author proposes a model for life extension and repair decision-making by the use of DHGF (Delphi-AHP-Grey Interconnect-Fuzzy Evaluation) theory. The author defines the DHGF method as:

> ”The DHGF algorithm is based on a combination of Delphi, Analytic Hierarchy Process (AHP), Grey Relational Analysis (GRA), and Fuzzy Comprehensive Assessment methods (...). DHGF is the combination of practical experience and scientific theory, and is a mathematics method from qualitative and quantitative view.” (Tan et al., 2016)

The Delphi methods objective is to predict what may happen in the future based on expert knowledge in a index system. This is performed by a set of experts and facilitators - the first step is deciding what shall be studied and then a set of questionnaires are sent out to the experts (Twin, 2019). Those must comment on the topics under review, giving input based on their experience and opinions. Later on the questionnaires are sent back to the facilitator’s team that processes the information given, analyse it and decide whether it is necessary to perform another round (Twin, 2019).

Analytic Hierarchy Process (AHP) is a method for multi criteria decision making. According to Thibadeau (2016), the method applies pairwise comparison of different alternatives based on a common criteria or goal, hence easily obtaining the relative importance of one situation over another.

> ”The elements are compared in relative terms as to their importance or contribution to a given criterion that occupies the level immediately above the elements being compared. The final weights of the elements at the bottom level of the hierarchy are obtained by adding all the contributions of the elements in a level with respect to all the elements in the level above” (Thibadeau, 2016).

The Grey Relational Analysis (GRA) derives from the concept of a system being grey, where the information available is limited (uncertain, unclear or incomplete) (Sallehuddin et al., 2008). Sallehuddin et al. (2008) defines that one great advantage of grey modelling is that it can handle very precisely this type of problem, working as an analysis tool whenever the information is insufficient to model the problem well. The GRA works well for problem solving in project selection and prediction analysis that require multi criteria decision (Sallehuddin et al., 2008), as is the case for life extension.

Fuzzy Comprehensive Assessment aims to capture uncertainties present at a system (Zhou & Chan, 2017) and decisions, specially those taken by humans. In simple logical tests, one assumes results as true or false, 0 or 1, with nothing in between, therefore considering there is no doubt about the model (Zimmermann, 2010). However, the more complex the system, the hard to model it, specially considering human capabilities - this is where fuzzy theory applies.

The DHGF methods combines these different theories to support decision making in a more efficient way, but it is not the only available tool. Shafiee et al. (2016) presents a framework that considers both technical and economical aspect. The author also states that in most cases, life extension is based only in technical or economical evaluations - not considered simultaneously - what can lead to incorrect results (Shafiee et al., 2016).

Life extension decision making is a multidisciplinary task, that involves inputs from different people with a set of variable knowledge - from engineers, operators and managers (Shafiee et al., 2016). Shafiee et al. (2016) also states that:

> ”Life Extension Management process must be defined taking into account not only economic factors such as maintenance expenditures but also technical requirements such as availability and survivability of Safety Critical Systems (SCE) during extended period of operation”

Shafiee et al. (2016) proposes to perform an asset condition assessment and then a cost benefit analysis to study the possibility of life extension of the safety critical systems. The decision is made by an index named ”Life Extension Measure” (LEM), calculated by the combination of economic and equipment health indexes, EI and EHI respectively (Shafiee et al., 2016).

The framework is divided into 3 phases. Phase 1 considers preparing for the study, where the criteria and objectives for life extension must be defined, as well as gathering the data and prioritizing safety critical systems. Phase 2 is the technical and economical analysis for life extension of each system and phase 3 consists of attaining regulatory approval and implementing the outputs of the frame work (Shafiee et al., 2016). Shafiee et al. (2016) tested out the methodology for a water deluge systems.

Risk analysis is also a tool to support decision making, and a study concerning structural repair of aging naval ships has already been performed by Liu et al. (2019). The authors described the process by first identifying the potential failure causes, and data gathering with design specifications, inspection records and maintenance plans. Then, the examination of possible life extension is done by a probabilistic risk analysis that links causes and consequences. A framework for repair decision making is also proposed (Liu et al., 2019).

Animah & Shafiee (2018) developed a framework to support decision making in the offshore oil and gas assets based on the condition assessment and useful life prediction, which was tested in a three-phase separator system. The authors proposed a connection between current technical condition of specific systems, remaining useful life prediction and a life extension management program based on the previous results for that specific system.

A risk analysis is performed to define the asset condition, considering operation condition, production loss, material degradation, fatigue cracks and corrosion. Later, the components are ranked and used to determine which ones shall have their useful life calculated. Animah & Shafiee (2018) also states that the method to calculate RUL varies upon a different set of criterion, and it should therefore be carefully selected so that good results can be achieved. The results of RUL allow for the decision making, where in most cases suitable decisions could be full replacement, or refurbishments and repairs of some systems.

This master thesis proposes a similar methodology as Animah & Shafiee (2018) for condition assessment tool and life prediction models. A tool is developed to assess the asset's “As Is” condition, with concepts based on expert opinion, and quantitative models are created - which in most case includes RUL calculations.

However, these data are treated as input into a simplified risk analysis that forecasts possible consequences of keeping the current condition during life extension period. Mitigation actions are proposed whenever risks are over the acceptable risk zone, which then become the decision making considering work scope. The methodology is tested out into some marine systems in a FPSO, and the results are gathered as work packs. A simple cost estimation is performed for all the created work packs, followed by an economical feasibility analysis to determine whether the unit would be a fit for having a longer life in operation than the one it was designed for.

Chapter 3

The FPSO Life Extension Methodology

This chapter summarizes the steps into the main master thesis development. It starts by giving a summary of the methodology for life extension, and presenting a diagram that links the theoretical research needed, the life extension methodology and a case study. Each of the main stages of the procedure are described further into the sections, which is organized into 7 phases.

The first phase consists on gathering the life extension requirements and defining important concepts. It is followed by characterizing a process to gather the asset condition and then phase 3 proposes the development of quantitative models to be used in the analysis. Risk analysis and risk mitigation actions are performed in phase 4, and phases 5 and 6 are dedicated to connect the information into work packs that can be costed. Phase 7 finishes by briefly giving an overview of how an economical analysis can be done to decide if the life extension project is feasible or not.

3.1 The Overall Process

The main objective of this thesis is to test out a procedure to support decision making in life extension projects of ageing FPSO units. The methodology development is iterative and divided into three main foundations - theoretical research, methodology development and a case study with a mock-up FPSO. The theoretical research is the basis to the tools creation to subsequently perform the life extension study. Therefore, it needs to be performed not only in the beginning of the thesis, but as issues come up along the development.

Different problems shall arise when the models are tested, hence a research is required to find solutions that interact with the methodology development and the case study. However, the thesis is presented in a linear way to facilitate the reader to understand it - first the theory is introduced, the tools are developed, then a fictional FPSO is described so that finally the methodology can be tested out. The process is divided into 7 main categories which are presented in Figure 3.1.

The first phase is named as life extension requirements, and is responsible for identifying what are the general constraints in a life extension project. This includes defining the main concepts needed and understanding what is critical during this type of project. Secondly, the general asset condition is evaluated, which includes a high level condition assessment of all the systems in the unit. This is important because it gives a condition overview of every systems, as well as allowing for a better understanding of what systems are requiring more attention. Then, quantitative analysis are performed including calculation of remaining useful life (RUL) for some marine systems and predicting equipment replacement and overhauls.

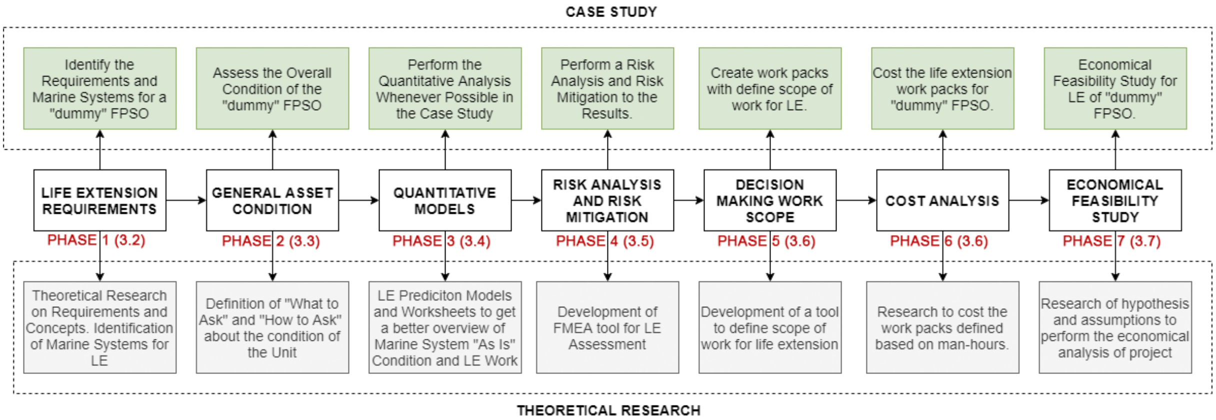


Figure 3.1: Diagram with Thesis Methodology.

With the asset's systems condition known and quantitative models developed, the next step is to perform a risk analysis of the effects during the extended operational life. This includes identification of possible hazards and failure modes, as well as performing a risk ranking in the outcomes. Whenever required and needed, risk mitigation actions are proposed. All the results from the systems should be gathered and a decision is to be made concerning life extension work scope.

The methodology follows by creating work packs, which are documents that list all the necessary work for a system to achieve a determined condition. Later, these work packs are measured in the form of man-hours so that a cost estimation can be made. Finally, the methodology concludes by performing a feasibility analysis into project economics.

As mentioned, the thesis is iterative - the models are created, tested and refined. Figure 3.2 presents the framework of the life extension methodology, and the next sections describe in more details each process.

The level of detail to which the thesis is extended to must also be established. It is common for engineering projects to be divided into concept, feasibility, preliminary engineering and detailed design, with increasing level of complexity respectively. This thesis shall have a detail level mainly in concept, and in some cases entering to feasibility level - hence dealing with qualitative and quantitative information. The FPSO is a very complex structure with a huge amount of systems, subsystems and components and a life extension study at any level is already very time consuming. As the thesis has a limited time frame, it was decided to keep it as high-level and only consider some of the asset's marine systems.

Apart from the phases of the methodology being iterative with each other, each phase has its own iterative procedure. Although each step is unique, they all have a similar workflow as presented in Figure 3.3. The necessary research is made into available literature, books and articles, followed by a discussion and questioning sections from the outcomes with the required personnel. Then, the specific tool or procedure for that phase is carried out and tested. If the outcomes are considered good enough, the methodology can proceed into the next phase, otherwise the whole procedure should be redone.

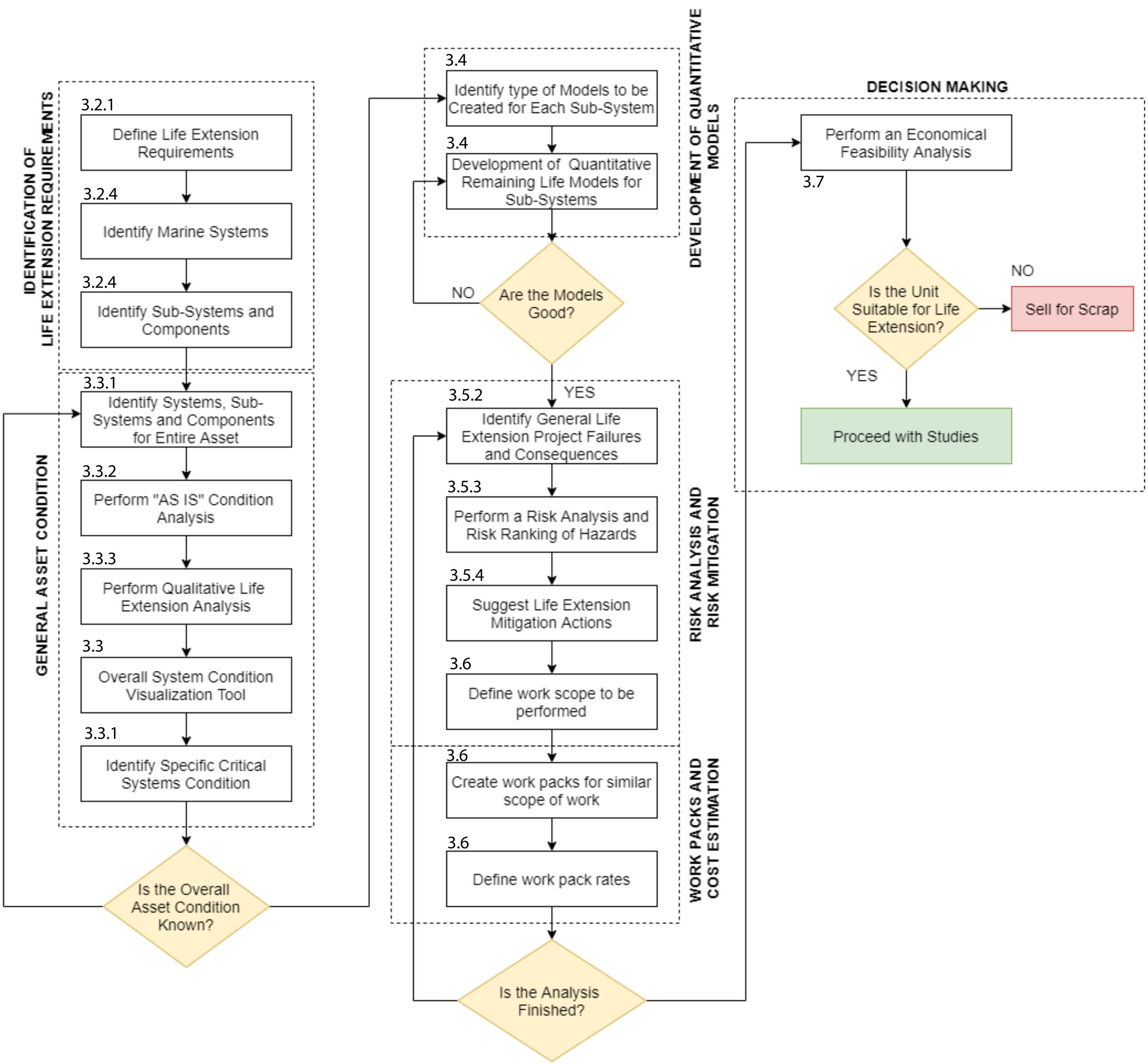


Figure 3.2: The Life Extension Methodology Framework.

When the methodology is finished, a case study is performed by using a FPSO. All the necessary information needed to perform the testing are defined, such as main dimensions, power equipment, field requirements and asset condition status. At the end, it is expected that the developed procedure is able to assist on deciding whether this vessel is suitable for having its life extended.

Aiming to test out the methodology developed, a mock up FPSO is defined. Some simple ship design techniques, such as regression analysis and 3D modelling are used to assist the description of the FPSO. The marine systems to be tested are also defined, but in a very simple manner. For instance the midship section selected is the one available in books, and engines, pumps and pipes were chosen based on information available online from different suppliers. A big effort is made to justify as much as possible the decisions, dimensions selected and analysis performed, but it was only possible to a certain extend - some very specific information's are not available on literature or online. Therefore, assumptions and hypothesis from different types were necessary to proceed testing the fictional vessel, such as establishing profit margins for ship owners and oil exploration companies and defining specific systems dimensions and capacities.

It is important to understand that, although the methodology has 7 phases, not all phases are applied in all systems identified. For example phase 1 is done as in an overall project level, while phase 2 is done for both the entire FPSO and then for each marine systems selected. Phases 3 and 4 are also done for each marine systems, while the work packs and their costs (phases 5 and 6) are created only after all the condition assessment is performed. Therefore, phase 7 is also done for the entire FPSO, hence uses as input all the information achieved before.

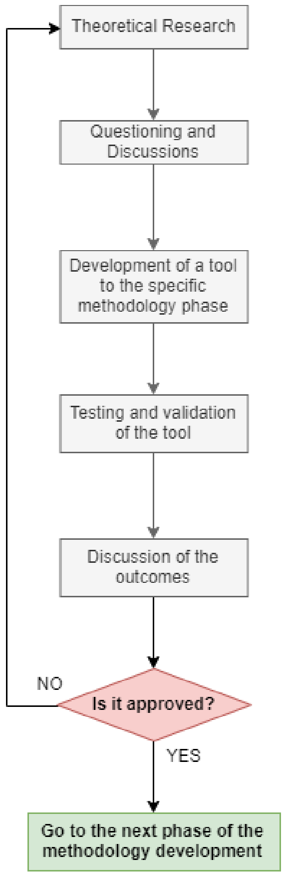


Figure 3.3: The Iterative Phase of the Methodology.

The master thesis is developed under the supervision of Odd Weisæth from Altera Infrastructure at the Early Phase and Innovation department. The topic emerged during the author's internship that started back in June 2019. Many personnel from different areas of Altera Infrastructure participated in discussions, giving diverse feedback's, suggestions and inputs throughout the master thesis development.

From NTNU, the supervisor is Henrique Gaspar and some topics addressed by this thesis are ship design, marine structures, shipbuilding materials, ship life cycle, marine systems engineering, risk analysis, and economical feasibility assessment.

3.2 Phase 1: Life Extension Requirements

Phase 1 defines some basic concepts that are needed for the thesis development, as seen on Figure 3.1. The first stage is in charge of defining life extension concepts and its variations, then the framework proceeds with evaluation of the life cycle of a life extension project and possible requirements. It follows with an overview of CAPEX and OPEX and finishes identifying the marine systems for life extension work.

3.2.1 Life Extension Work, Life Extension Project and Redeployment Project

When a FPSO contract is approaching the end, the operator needs to perform a business evaluation and decide what should be the destiny of the asset in question. As previously stated in Section 2.3 and Section 2.4, there are a few options that must be considered in this stage of the unit's life cycle: scrap, sale, redeployment or life extension - and the ship owner decides on the most economically beneficial.

Before proceeding with the methodology, however, it is important to clearly define what life extension is and how it is addressed in this thesis. Life extension is used from now on in two different aspects: life extension project and life extension Work. This is needed because a redeployment project requires life extension work but is different than a life extension project.

Life extension works are the procedures performed after a specific system, subsystem or component has reached (or is close to reach) its design life, with the objective to increase the operational life. It is done based on a set of requirements that are treated as inputs. After life extension works are performed, the element in question can have its performance restored to original one, or palliative actions can be carried out to extend the operation for a defined period of time.

Once the unit is being analysed to stay at the same oil field, there will be no new requirements considering the FPSO design. However, as the unit has most probably been in the location for a long time, the operator needs to prove that the asset is capable of operating safely. Hence, the life extension works carried out are based on the same set of requirements as for the original FPSO design.

3.2.2 Life Extension Project Requirements and Life Cycle

The previous section defined the differences on how the life extension concept is used and from now on this thesis focus solely in FPSO life extension project.

To get approval for the life extension, an overall assessment of the FPSO condition must be performed and the work required to acquire the necessary level of safety must be known. Therefore, it is not only the technical condition of each system and what must be done to extended their operational life that must be acknowledged, but all the new regulations that came into practice since the FPSO was firstly designed.

The type of work included in a life extension project are mainly summarized in Figure 3.4. Life extension works includes structural modifications and repairs, replacement of obsolete equipment (Life Extension - Obsolete) and structural surface treatment, such as painting/coating. For example, replacement of obsolete telecommunication equipment or structural repairs and modifications in the hull are categorized as life extension work.

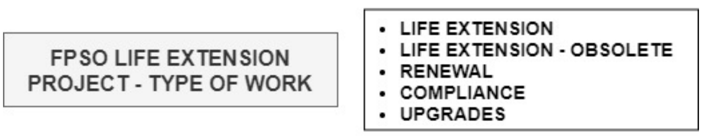


Figure 3.4: Types of work at a life extension project.

Renewal is the work scope that deals with the status of the system or equipment due to the unit's operation and maintenance. It can include, but is not limited to, replacement of entire or parts of a systems due to corrosion, or even repairs. Compliance is the work related to obtaining class certification and regulatory compliance for the asset. Upgrades are the work that cannot be classified as life extension nor renewal but can be done to improve operability.

The life extension project is a multidisciplinary task, i.e. it involves marine engineers, naval architects, process engineers, maintenance and operational crew, and business managers. Each group of people has a unique set of skills that when put together leads to a successful life extension project. Like any marine engineering project, it involves many stakeholders such as the shipowner, operator, oil company, classification societies, insurance companies, inspection companies and engineering service providers. In order for the project to go as smooth as possible, a project manager or a project management team is needed to coordinate it. It is also necessary to mention that, as the project evolves from concept phase to detailed design, more information will need to be addressed and thus it becomes more complex.

As seen on Figure 2.5, the level of detail increases as the engineering project moves forward in its life cycle. Due to the limited time and type of the master thesis selected, it was decided to keep the analysis categorized as “high level”, hence navigating between Concept and Feasibility level. Some of the assessments made are merely qualitative and based in simple hypothesis, while others are guided by engineering calculations and analysis.

3.2.3 CAPEX and OPEX

CAPEX and OPEX are business concepts very useful to evaluate life extension projects. According to Amado (2013), CAPEX stands for “Capital Expenditures” and is the investment that is made before the production starts. Considering CAPEX for an oil field, it includes all the investment to get an the field working, like the costs related to well drilling, subsea manifolds, pipelines and asset construction (Amado, 2013). CAPEX for life extension project does not include the subsea systems nor new drilling, once all the infrastructure is already in place. Also, CAPEX here refers to the shipowner/operator who is just leasing the vessel. Therefore, it mainly considers the investment related to extending the unit’s life.

The OPEX means “Operational Expenditures” and refers to the monetary amount needed to keep the vessel working in normal business operation (Amado, 2013; Kenton, 2019). It includes crew salary, taxes, maintenance, repairs expenses, consumables costs, helicopters, crew travelling, supply boats and so on. According to Kenton (2019), reducing the OPEX cost is a challenging task because it can impact the quality of the asset’s operation. Nevertheless, when performed successfully it can increase the revenue’s.

The concepts of CAPEX and OPEX are very clear and defined by traditional literature, but in practice things are much more complex. As a company, the business responsible for the unit wants to reduce its costs and increase the revenues as much as possible. The outcomes of the asset condition and an estimation of remaining life are critical information for the management team, as they help the decision making on whether that work should be carried out before or during the new operational time frame. If it is done before, this should be considered as part of CAPEX, while when performed during regular operation it is an OPEX price. This decision should address the impacts in operation, once if the unit is shut down it does not produce and therefore is not paid.

3.2.4 Selected Marine Systems

As seen on section 2.1, there is a huge amount of systems inside a FPSO, each with its own degree of complexity. Due to narrow time, the thesis scope of work must be limited and therefore it is not possible to assess both marine and process systems. Considering that the MSc is based on Ship Design disciplines, it was decide to develop the methodology only for some FPSO marine systems.

To define what systems should be evaluated further, a screening parameter is selected: availability of information. After researching on suppliers websites, marine engineering books and articles, the marine systems to be assessed were bounded into five groups: structural systems, firefighting systems, offloading system, power generation system and telecommunication systems. Explaining how each system works in detail is out of the scope of this thesis. However, the following sections explain briefly what are the potential failure modes for each and propose how a quantitative assessment can be performed. In Chapter 4 , the systems are described with the necessary level of detail required for this project.

The assessment considers two system levels - the marine system is classified as level 1, and the subsystems are classified as level 2, as can be seen in 3.5. Level 2 is defined as main subsystems because those are the more relevant ones to the analysis. The control systems are classified as subsystems present in each marine system and therefore are not assessed as a level 1 system.

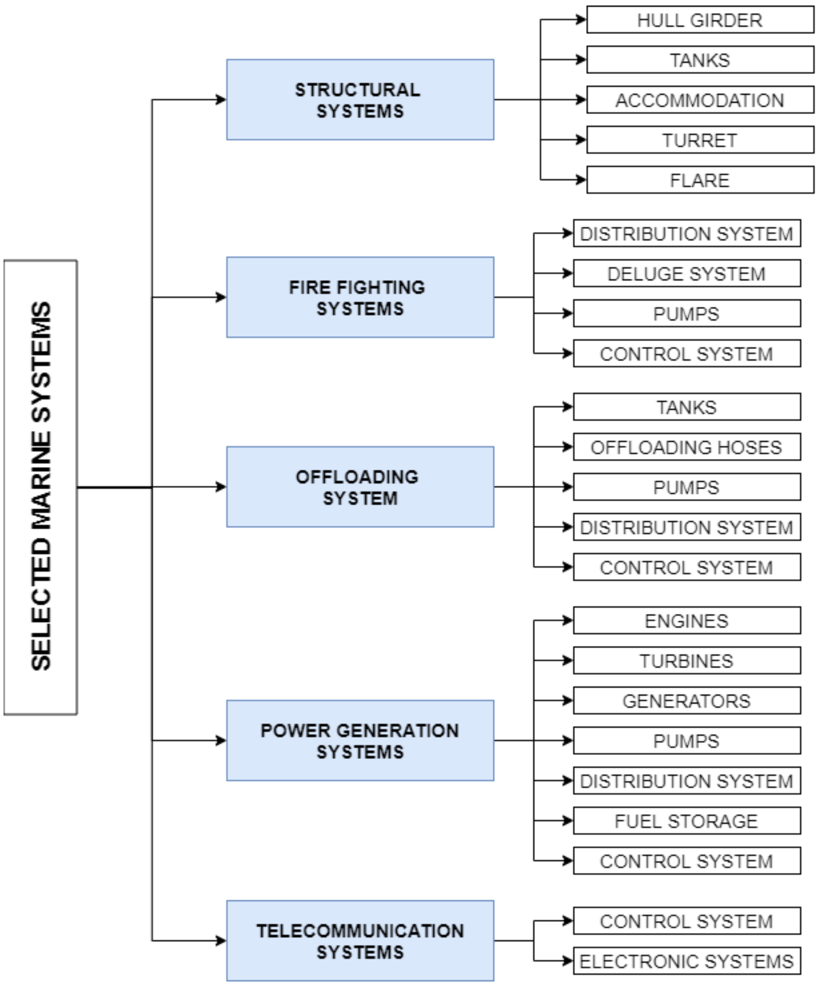


Figure 3.5: The Selected FPSO Marine Systems.

3.3 Phase 2: Asset Condition and Life Extension Scope Assessment

The second phase in the methodology proposed refers to the general asset condition and life extension scope of work, as presented on Figure 3.1. Although some of the marine systems are already identified, it is also imperative to have information on the other systems onboard the unit. Here, the development of a tool is proposed - a spreadsheet - that can perform a qualitative evaluation of the entire FPSO condition and identify some possible scope of work. Figure 3.9 summarizes Phase 2 in a framework.

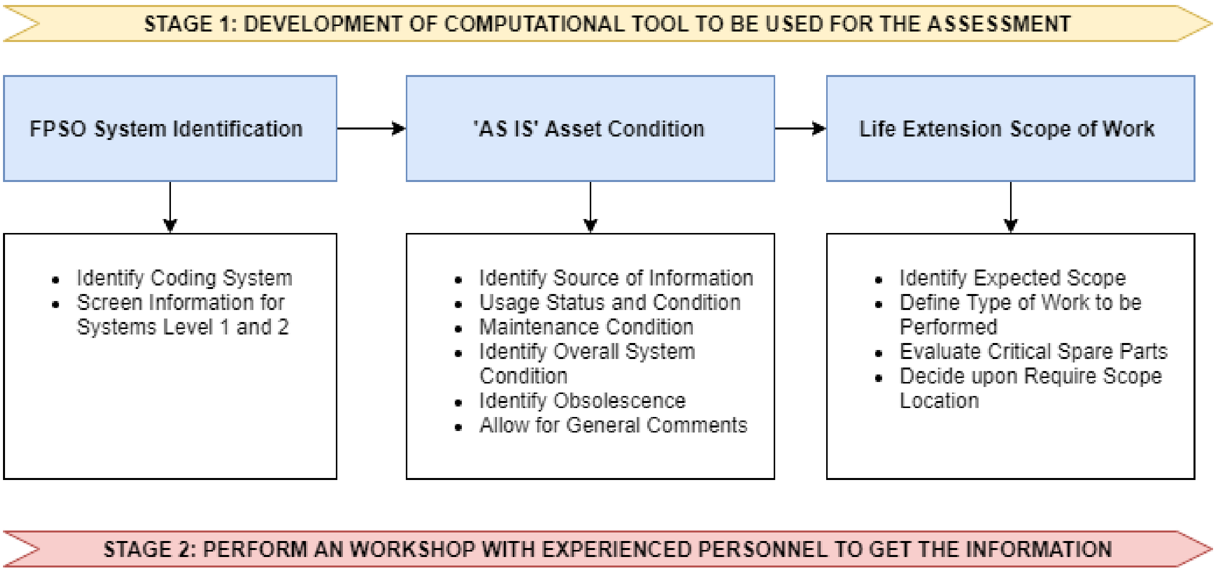


Figure 3.6: "AS IS" Asset Condition and Life Extension Scope Work Flow.

The process is categorized in 3 parts, and to be carried out in 2 stages. These 3 parts are the main analysis to be done - one is related to identifying the coding systems used, then performing a qualitative assessment of the systems' conditions and later defining some information about scope of work. Stage 1 is the development of a tool to be used in Stage 2, the analysis. First a template is created and then information on the asset's condition are defined.

Each part of the framework is explained next. As a computational tool is used, it is possible to create info-graphics, filters and group the data based on the information provided. For instance, one can find knowledge on how many systems are bad or good, and where is the life extension work scope going to be performed. The outcomes of Phase 2 also allows the management team to identify what subsystems are in a worse condition and require deeper analysis.

3.3.1 FPSO Systems Identification

Over the years, the amount of systems in the units increased and the industry started to standardize their naming. The most well known and used coding systems are the NORSOK standards and the SFI Coding and Numbering System. An example from the NORSOK coding is presented in Figure 3.7.

It is important to notice that, although the numbering is standardized, there are a few differences from unit to unit. In consequence, it is necessary to analyse and extract the correct information from the FPSO that the assessment shall be made - it is not possible to assume every single FPSO has the same identification coding. Figure 3.7 also presents the top-down approach used to develop the asset condition tool - where the information is to be obtained for levels 1 and 2 mainly. This is in accordance with Figure 3.5, that presents the main subsystems to be studied.

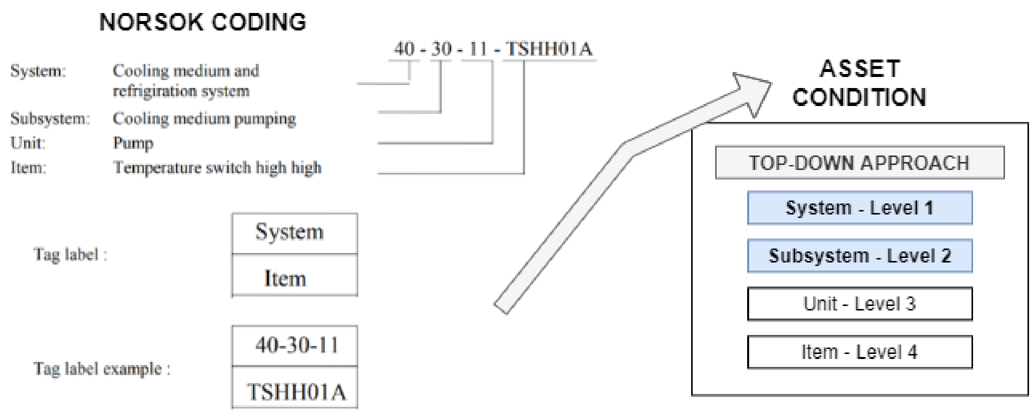


Figure 3.7: NORSOK systems numbering (NORSOK, 1995) and the Asset Condition Top-down Approach.

In an offshore shipping company, there are different sectors responsible for the day-to-day maintenance of a vessel - from the crew onboard to the team onshore. However, the people with the best knowledge of the actual condition of the unit are definitely the ones dealing with it directly: the maintenance crew. With the objective to facilitate the understanding of offshore crew, the most relevant coding language to them is to be used. Thus, the identification of the systems should be based on a maintenance software whenever applicable.

3.3.2 "As Is" Asset Condition

With the systems processed and gathered at a template, the next step is to build up a structure to understand the full asset condition by evaluating each system individually. This considers only the current condition of the unit, and is therefore named as "As Is" condition. To understand what are the main information needed in a life extension project, discussions with experienced personnel at Altera Infrastructure in Trondheim were conducted - inputs and suggestions were received from people in maintenance, operations and early phase departments. The outcome was the development of a series of different questioning to be inserted into the tool, where the user can decide upon one of the options based on drop down lists, and only a few would allow for free text filling.

The first questioning refers to the where or whom is that information coming from, i.e. identifying the source of the information which can be the maintenance software, classification societies reports, vendor/supplier, risk based inspection surveys or personnel experience. This is useful in order to filter the information available and even perform a quality check into the inputs.

Then, the usage and usage status shall be assessed. If the system is in use, the user is allowed to choose whether it is working according or below specifications. If the system is not in use, the user must choose if it is broken or the use is not required. The maintenance status must also be informed: if it is maintained, if there is a backlog in maintenance or if it is not maintained at all.

Another important questioning made to the user is the overall condition of the system. The user must choose among good, average - unknown condition, average - further inspection to be defined, bad or upgrades required. Obsolescence is a key issue in life extension projects, thus it is also assessed during the asset condition phase - a yes or no must be given to whether the system is obsolete. If the user desires, a comment section is available to justify or provide more description into the condition of the element.

Information Source	Usage	InService	Maintenance	Condition	Obsolete	Comments	Date
Maintenance Software	InService	Working According to Specs	Maintained according to Maintenance Software	Good	Yes	Frre Text	Free Text
Vendor	NotInService	Working Below Specs	NOT Maintained	Average - Known Status of the System	No		
RBI		Broken	Backlog Maintenance	Average - Further Inspection to be Defined			
Class Society		Use not Required		Bad			
Personnel Experience				Upgades Required			

Figure 3.8: Condition Assessment (Courtesy of Altera Infrastructure).

3.3.3 Life Extension Scope of Work

After filling the information regarding the asset condition, information about work scope for possible extension of contract should be provided. The tool can be used when a life extension period is already defined, or to simply keep an updated information database. Again, discussions were conducted in Altera Infrastructure and feedback and inputs were received from the personnel that helped shape this tool.

The life extension assessment requires information on the expected scope, if the system has critical spare parts, what type of work is necessary and where it can be done. In the expected scope section, the user has freedom to fill in text information about what work is required in case of extension of contract. Needing spare parts can be crucial at life extension projects, because if a component must be replaced in the future and there is no more available parts, it can become necessary to replace the whole system - thus, yes or no must be answered.

The scope of work section is divided into life extension, life extension - obsolete, renewal and upgrades. The difference between each one was explained back in section 3.2.1. During the project, it is important to evaluate carefully where the work shall be carried out, as dry docking and yard stay are expensive. Hence, required scope location should also be informed by choosing between drydock, yard stay, offshore campaign requiring production shut down, included in regular maintenance programs or to be performed during layup period.

EXPECTED SCOPE	TYPE OF WORK	CRITICAL SPARE PARTS	REQUIRED SCOPE LOCATION
FILL IN TEXT	LIFE EXTENSION	YES	DRYDOCK REQUIRED
	LIFE EXTENSION - OBSOLETE	NO	YARD STAY REQUIRED
	RENEWAL		OFFSHORE CAMPAIGN REQUIRING PROCESS SHUTDOWN
	COMPLIANCE		INCLUDED IN MAINTENANCE PROGRAM
	UPGRADE		LAY-UP

Figure 3.9: Scope of Work Assessment (Courtesy of Altera Infrastructure).

3.4 Phase 3: Development of Quantitative Models

From Figure 3.1, phase 3 in the methodology is the development of quantitative models, which are really useful when performing any engineering assessment because they return a number that can easily be costed, . However, one unique quantitative model for each selected marine system is not effective, as it can be seen that many subsystems repeat for different main systems. Hence, it is necessary to evaluate each one and identify what are the main components and failure modes, so that a calculation model can be proposed in a more efficient way.

Figure 3.10 breaks down the main subsystems of the marine systems into four different categories: structural components, pipes, rotating equipment and electronic systems. Phase 3 of the life extension methodology will assess the possibility of creating quantitative models based on empirical formulations for the components identified.

Each component is studied next, presenting the typical ageing failure modes and proposing computational models to evaluate it. The common objective of all analysis is to have an overview of how it will behave during the life extension period, thus forecasting what will be its condition.

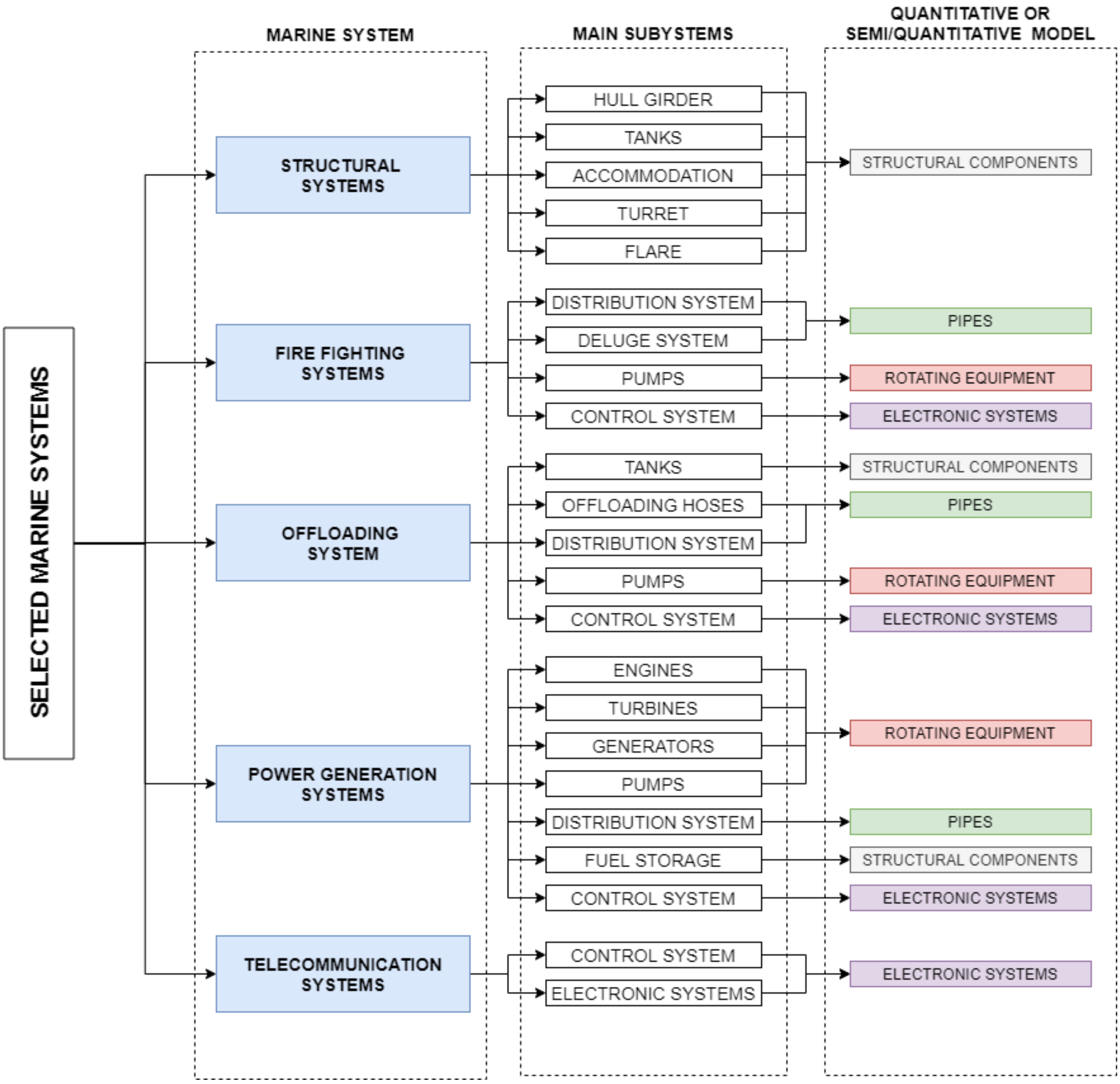


Figure 3.10: Definition of Quantitative and Semi-Quantitative Models to be created.

3.4.1 Structural Components

Although there are different structures in structural systems, such as the hull girder, tanks, accommodation areas, turret and flare, they are all very similar. Hence, to create an effective analysis method, the structural components were roughly divided into three members: steel plates, steel stiffeners and welds.

According to Paik & Thayamballi (2007), typical age-related deterioration problems found in marine structures are corrosion, fatigue cracks, dropped objects and impact damage, and coating breakdown. Each of the structural members are subjected to all of the deterioration factors, as presented in Figure

3.11.

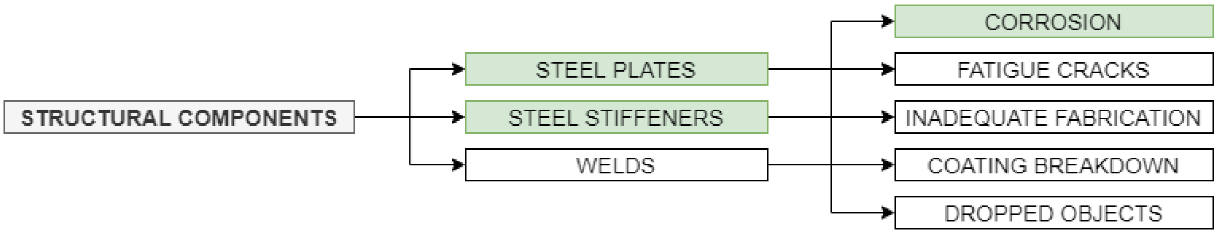


Figure 3.11: Definition of Structural Elements and Age Deterioration Factors.

The structural assessment can become very extensive and complicated, requiring finite elements analysis for complex assessment. As the objective of the thesis is to assist in the early phases of a life extension project, it was decided to choose a few elements and one failure mode to be addressed: steel plates and stiffeners predicting corrosion effects into their thickness. The procedure is a general analysis on calculating how much time is left based on corrosion rates, and it can be applied to any of the structural systems presented before.

It is important to address corrosion wastage of steel plates in marine structures because the vessel's ultimate strength can be reduced (Paik & Thayamballi, 2007). Two types of corrosion usually affect offshore vessels: general and pitting corrosion. The general corrosion assumes that the effects are uniform all over the plate, thus the thickness is reduced everywhere. Pitting corrosion, however, reduces the thickness at a specific location in the plate (Paik & Thayamballi, 2007) - the thesis addresses general corrosion.

In principal, the thickness of the structure is governed by Equation 3.1, where t_{final} is the plate thickness after corrosion, t_0 is the initial thickness, i.e. the design or gross thickness thickness and $t_{corrosion}(t)$ is the corroded amount. This equation is defined as a function of time, because the longer the asset's exposure in a corrosive environment, the higher is its exposure to corrosion effects.

$$t_{final}(t) = t_0 - t_{corrosion}(t) \tag{3.1}$$

Also, coating is applied in marine structures so that the corrosion effects can be reduced. This should be taken into consideration when predicting how much useful time is left to the unit, as the coating layer has also a life time.

Paik et al. (2003) developed wastage models as a function of time to help predict the effects of corrosion in single and double hull tankers. The FPSO structure may resemble a tanker structure, but these two units present different structural flexibility and load patterns. According to Paik et al. (2003):

> "The structural characteristics of ocean going single or double skin tankers may be different from those of FSO's or FPSO's, which load and unload a lot more frequently, sometimes every week. Such frequent loading/unloading patterns of FSO's and FPSO's may accelerate the corrosion progress. On the other hand, FSO's and FPSO's typically operate standstill at a specific sea site, and this aspect may likely mitigate the dynamic flexing, keeping the corrosive scale static, compared with that of oceangoing vessels. The two counter aspects may then offset the positive and negative effects." (Paik et al., 2003).

Furthermore, the author also states that the tanker models can be used to predict corrosion effects in FPSO's, as long as the environmental conditions are similar. This thesis proposes to use some of the framework defined by Paik et al. (2003) while checking the final condition to *DNVGL-CG-0172: Thickness Diminution for Mobile Offshore Units*. Whenever more accurate corrosion data is available to predict the wastage over time, it should be used.

The framework for the analysis is presented in Figure 3.12 and is explained in details in the next sections. At the end, the assessment provides an estimation of how long it will take until the unit reaches the minimum allowable thickness before steel renewal has to be carried out.

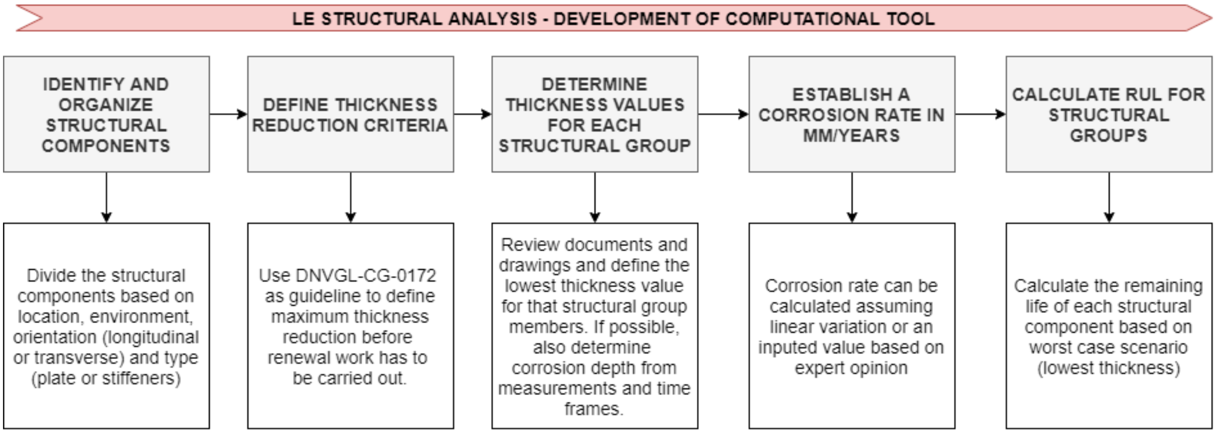


Figure 3.12: Framework for Life Extension Analysis of Structural Components

Identify and Organize Structural Components

The analysis should start by organizing and grouping the structural members, using the same logic as performed by Paik et al. (2003). The authors identified 34 different groups, presented in Figure 3.13 - this is for an oil tanker, not a FPSO, therefore should be used as guidance to organize the information from the asset. The full assessment is illustrated on Appendix A.1 - Structural Components, and a a similar procedure is be done to the FPSO.

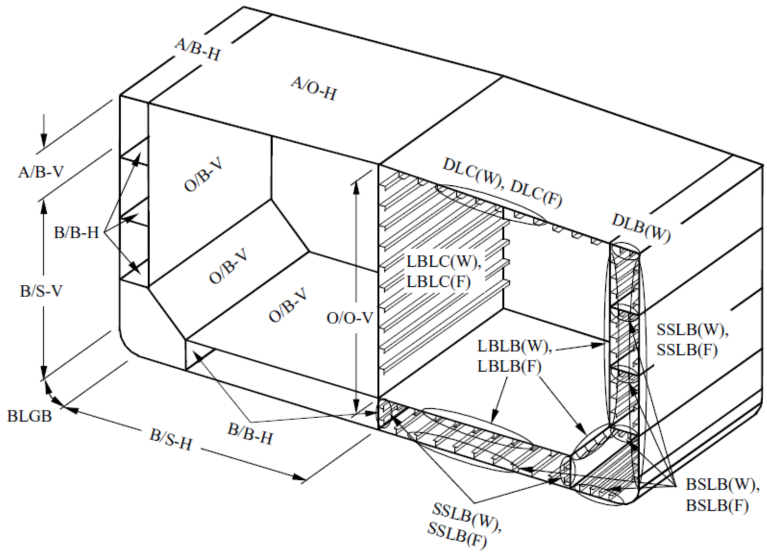


Figure 3.13: Midship Section with Member Groups (Paik et al., 2003).

The author defines that the identification is guided by environment, location, and type of longitudinal stiffeners. The environment is dived into A=Air, B=Ballast Water, O=Oil and S=Seawater. The location is organized into V=Vertical and H=Horizontal, while the longitudinal stiffeners are W=Web and F=Flange (Paik et al., 2003).

Define Thickness Reduction Criteria

DNVGL-CG-0172: Thickness Diminution for Mobile Offshore Units proposes the use of a "Diminution Coefficient, k, to calculated what is the allowable thickness reduction before a renewal must be carried out in a structural member". The renewal thickness, t_{ren}, is calculated by Equation 3.2 and is the criteria to later calculate the remaining life.

$$t_{ren} = k * t_{gross} \tag{3.2}$$

k is the Diminution Coefficient and t_{gross} is the gross thickness, that can be found as presented by Figure A.3 in Appendix A.1 - Structural Components. It is assumed that t_{gross} is t_d, i.e. the design thickness that should include minimal design thickness, corrosion allowance (coating) and corrosion margin from operator when applicable as can be seen in Figure A.3. The correct value of k must be identified for each type of strength member, which are also available on Appendix A.1 - Structural Components.

Determine Thickness Values for Each Structural Group

With the members grouped, the values for the different types of thickness should be established. It is possible that there are different values of design thickness throughout the different stiffeners and plates grouped together, i.e. the B/S-H (Horizontal Bottom Shell Platting between Sea Water and Ballast Water) can be designed with different plate thickness. Hence, to be conservative in the analysis, the lowest value of t_d should be selected. The same applies for the t_c, coating thickness - the lowest value in the group should be used for further analysis.

If coating is assessed as proposed by Paik et al. (2003), it is also required to identify the time frames, where T is the total exposure time, T_c is the coating life and T_t is the transition time, i.e. the time between the end of the coating life and when the corrosion starts. When this information is not available, coating effects on corrosion can be assessed based on guides from classification societies.

Establish Corrosion Rates in mm/year

The key factor into the analysis is defining the annual corrosion rates for each member group. This can be done based on statistics analysis when it is available, or by regulations and experts opinion.

Paik et al. (2003) gathered more than 30,000 values of corrosion depth measured by instruments from over 200 trading tankers. The authors performed statistical analysis for all the groups defined before, and considered a coating life of 5, 7.5 and 10 years. Severe and average corrosion rates were calculated, and are presented in Appendix A.1 - Structural Components, with a comparison to the values proposed by TSCF (Tanker Structure Cooperative Forum). More information on the methods of analysis can be found on the book "Ship Shaped Offshore Installations" (Paik & Thayamballi, 2007).

If data is available on corrosion measurements for the specific unit, the analysis can be made assuming corrosion over time. Using the Equation proposed by Paik & Thayamballi (2007), the annual corrosion rate for a specific group is calculate as:

$$C = \frac{t_r}{(T - T_C - T_t)}(mm/year) \tag{3.3}$$

When none of the above is considered applicable, the team performing the assessment can lookup common practices in the industry or ask for expert opinion on what value of corrosion rate should be used.

Calculate RUL for Structural Groups

The remaining useful life, RUL, is calculated by forecasting how long the steel member lasts before reaching the renewal criteria. This is done by calculating a corrosion allowance and dividing by the corrosion rate, as presented in Equation 3.4.

$$RUL_{StructuralMembers} = \frac{t_{current} - t_{ren}}{C} \tag{3.4}$$

A parameter $t_{current}$ is included because in principal, remaining useful life is calculate to the 'As Is' condition of the unit. Therefore, the thickness values should be found in inspections reports. If the t_d is used, one is actually forecasting the total life of the structure, and not the remaining life.

3.4.2 Pipes

After research on available literature and discussions with experienced personnel, it was set to evaluate the pipe corrosion degradation over time. This is done by predicting how much wall thickness is corroded during the operational time and what would the effects on life extension be.

During pipe design, there are usually three sets of pressures to be analysed P_D, P_{SV} and P_{OP}. According to NORSOK Standard Process Design P-001 (NORSOK, 1997), the P_D is the maximum pressure, internal or external, that must be used in order to determine the minimum wall thickness in the pipe, P_{OP} is the pressure during operation in steady state condition, i.e. the regular operating pressure of the system, and P_{SV} is pressure safety valve. As a design requirement, different safety factors are included while designing the piping systems, meaning that the design pressure has always the highest value, while the operational pressure must always be lower than the other two, as presented in Equation 3.5.

$$P_{DN} > P_{SV} > P_{OP} \tag{3.5}$$

Hence, three different minimum allowable wall thickness (MAWT) could be used in the analysis: t_D - MAWT Design Pressure, t_O - MAWT Operating Pressure and t_{SV} - MAWT Safety Valve Pressure. Besides those, another criteria has to be determined: a maximum corrosion allowance. The outcomes of the assessment is similar to Section 3.4.1 but now the results are the remaining life of the pipe. Figure 3.14 presents the framework for the pipe assessment, which is divided into four stages that are discussed next.

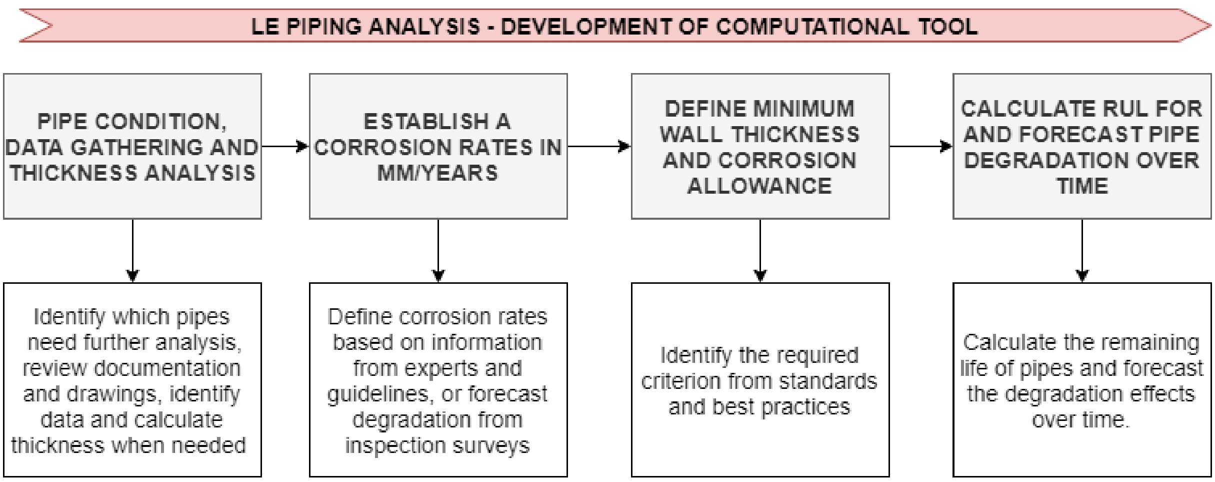


Figure 3.14: Framework for Life Extension Analysis of Pipes.

Pipe Condition, Data Gathering and Thickness Analysis

The analysis starts by understanding what pipes need a further assessment and by gathering the required information. The outcomes of the asset condition should be used to identify which systems are in poor condition and need a deeper evaluation. Then, documents and drawings need to be gathered and information identified. Some of the information needed are pipe diameter, type of fluid, pressures and thickness.

When the required data is not available, design guidelines can be used. For instance, the value for t_D, can be calculated based on guidelines by *DNVGL - Rules for Classification of Ships - Part 4 Systems and Components - Chapter 6 Piping Systems* (Veritas, 2008). The code proposes that the minimum allowable wall thickness cannot be less than Equation 3.6:

$$t = t_0 + c \tag{3.6}$$

$$t_0 = \frac{P_D D}{20\sigma_t e + P_D} \tag{3.7}$$

Where t is the minimum allowable wall thickness, t_0 is strength thickness and c is the corrosion allowance. The t_0 is calculated by Equation 3.7, with P_D refereeing to design pressure, D pipe external diameter (mm), σ_t permissible stress (N/mm^2), and e is the strength ratio and this equation is valid for pipes with $\frac{t}{D} \leq$ 0,17.

The code defines that the permissible stress must be based in the lower value from the conditions presented in Equation 3.8 and Equation 3.9, where σ_b is the specified minimum tensile strength of the material in N/mm^2 at a temperature of 20$\deg$,σ_{ft} is the specified minimal yield stress 0,2% proof stress of the material at design material temperature (N/mm^2) and $\sigma_{b100000}$ is the average stress of rupture after 100 000 hours at the design material temperature (N/mm^2). For simplifications, it is assumed that the pipes are seamless or welded pipes, and the code also proposes to use $e = 1$ for welded pipes produced by manufactures that can be considered as seamless, or $e = 0,9$ for welded pipes from other manufactures (Veritas, 2008).

$$\frac{\sigma_b}{2,7} \text{ or } \frac{\sigma_{ft}}{1,6} \text{ for austenitic} \tag{3.8}$$

$$\frac{\sigma_{ft}}{1,8} \text{ or } \frac{\sigma_{b100000}}{1,8} \text{ for other materials} \tag{3.9}$$

Adapting the equations to fit not only design pressure but also the safety valve pressure and operational pressure, one can find:

$$t_D = \frac{P_D D}{20\sigma_t e + P_D} + c \tag{3.10}$$

$$t_{SV} = \frac{P_{SV} D}{20\sigma_t e + P_{SV}} + c \tag{3.11}$$

$$t_D = \frac{P_O D}{20\sigma_t e + P_O} + c \tag{3.12}$$

Establish Corrosion Rates in mm/years

With the thickness defined, the corrosion rates during the operational life of the pipe must be obtained. There are mainly two ways to calculate corrosion degradation over time: assuming a linear distribution and using a corrosion rate of $mm/year$ or performing a forecast based in historical data.

The first option is a simplification of corrosion degradation, and corrosion rates can be found from guidelines, such as *DNVGL-RP-G101 Risk Based Inspection of Offshore Topsides Static Mechanical Equipment*. Although the focus should be a marine system and not the process one, this guideline is considered feasible due to the lack of other information available.

As the focus is in the marine pipes, there are basically three liquids to be considered inside the pipe: seawater, freshwater and oil. If historical data about corrosion inspection is available, then a forecast can be made. The information shall be inserted into a spreadsheet and regression analysis shall be performed, choosing the best equation that fits the data available. For external pipe corrosion, the marine environment is used as primary actor, and the same guideline to define internal corrosion rates can be used. Also, pipes are considered coated, externally and internally.

Define Minimum Wall Thickness and Corrosion Allowance

The MAWT calculated in Equation 3.6 was defined before but is also necessary to cross-check the values found with some standard parameters defined by DNV, as presented in Appendix A.2 - Pipes, Figure A.9. The corrosion allowance factor, c, varies based on pipe material type and liquid. Table 3.1 from DNV guidelines present a range of different factors with different applicabilities.

Corrosion Allowance c for Steel Pipes	
Piping Service	c (mm)
Superheated steam	0,2
Saturated steam	0,8
Steam coils in cargo tanks	2
Feed water for boiler in open circuit systems	1,5
Feed water for boiler in closed circuit systems	0,5
Blowdown pipes (for boilers)	1
Compressed air	0,3
Hydraulic oil	0,3
Lubrificating oil	1
Fuel oi	2
Cargo oil	0,3
LPG	0,3
Refrigerants	0,3
Freshwater	0,8
Seawater in general	3

Table 3.1: Corrosion Allowance for Steel Pipes According to Veritas (2008).

The methodology proposes the use of 4 parameters to analyse pipe corrosion - whenever enough data is available, one can perform the analysis completely. However, when it is not possible to define the different pressures, one should focus on corrosion allowance as main criteria. The analysis utilizing the different pressures is justified as it allows for risk assessment. Knowing location of pipe and comparing thickness from design to operation pressure can help to choose whether to fully substitute the pipe or not.

Calculate RUL and Forecast Degradation Over Time

Once the data is gathered and the criterion defined, the study on life extension can begin. With initial wall thickness known, the corrosion degradation is subtracted from it. Equation 3.13 presents the formula used to predict the wall thickness over the life extension period, where t_0 initial wall thickness defined before and $c'(t)$ is the corrosion degradation.

$$t(t) = t_0 - c'(t) \tag{3.13}$$

The expected behaviour is that the initial value for t_0 is above t_D, as t_D should be the minimal thickness while t_0 includes allowance and safety factor. After some time, the wall thickness will get smaller, going below acceptable levels or not. An example for the proposed methodology with forecasting and possible analysis with different thickness values is available on Appendix A.2.2 - Pipe Methodology Illustration.

The RUL can be calculated by the same equation proposed for the structural analysis, but now there are different values - one for each pressure and criterion as presented in Equation 3.14. Again, same idea expands here considering the time of initial thickness measures - if one is using the latest inspection report values, then a remaining life is being calculated. Otherwise using a design thickness, one predicts design life.

$$RUL_{Pipes} = \frac{t_o - t_i}{C_i} \tag{3.14}$$

3.4.3 Rotating Equipment

In the offshore industry, it is common to define rotating equipment as everything that moves product - that is gas, oil and water (Forsthoffer, 2006). Rotating equipment are pumps, engines, turbines and generators. When designing a vessel, the rotating equipment are not normally designed, but selected based on a set of established criteria, as for example required power ranges and flow rates.

Consequently, the rotating equipment are treated as products brought into the vessel that need to be integrated with the other systems. They are devices provided by manufacturers whom defines a set of maintenance guidelines for the equipment, as well as a limit of maximum running hours before a complete overhaul or replacement - how long the engine can run without major problems.

Overhauling an engine means completely assessing its condition, cleaning what is necessary and substituting components that have been worn out. Once the overhaul is complete, the engine system should be restored back to manufactures specifications. According to Pascoe (2000), the overhauling process can include replacement or repair from bearings and cylinders liners, heads and valves, to thermostats and pumps.

The life extension analysis for rotating equipment is based on calculating remaining component life and time between overhauls. To illustrate the procedure proposed, it was decided to use a a four-stroke diesel engine, Wärtsilä 46F, for HFO1 fuel type. Some assumptions and hypothesis were made to create a scenario for the analysis. The engine is composed by cylinders, water cooling pumps, exhaust valves, piston, camshafts and more. Information on overhauls and life time can be found on Appendix B.3 - Power Generation System - those are the used values to generate the diagrams in this section.

Define Component Life and Overhauling Periods

The procedure starts by reviewing manufacturer documents and maintenance information. It is fundamental to identify what are the proposed overhaul times and components life from manufacturer's maintenance guidelines.

Then, the maintenance already performed by the crew has also to be known, as depending on the operating life span, overhauling and replacements can have already been performed. The main components for each rotating systems being analysed should be inserted into a spreadsheet, along with all the information in overhauls and replacements. Generally, this stage is defined as data gathering for the next analysis.

Therefore, assuming that these values can be found from manufactures information, the expected life time and time between overhauls and inspections are treated as inputs. As stated before, the operator is also aware of how long the engine has been operating, which is also treated as an input. Hence, a simple analysis can be performed to predict useful life before overhaul or full replacement.

Calculate Remaining Life and Time for Next Overhaul

There are different expected life times for all the components of the engine - depending on their complexity, it can take much longer or much shorter time for needing replacement. In a life extension assessment, it is important to know how much time is left for each one. Also, it is assumed that as those components reach their expected life time, they are replaced for a new one. Thus, the new components will have the same running hour length as before. The remaining life time analysis is summarized in the first part of Figure 3.15. The same analysis as presented for remaining life can be extended to predict when the engine will need a new overhaul, as schematically shown in the second part of the same figure.

Figure 3.15: Predicting RUL and Next Overhauling for a Component of a Diesel Engine.

Using Wärtsilä 46F as an example, one can predict the remaining life of the components (ELT - Estimated Life Time) and next overhaul by the proposed methodology. Considering an operation time of 40000 hours and life extension period of 31000 hours, the results for the three components listed below are as follows:

"AS IS" CONDITION			
Component	ELT (hours)	RUL (hours)	Next Overhaul (hours)
Twin pump fuel injection			-
- Injection Nozzle	6000	2000	-
- Injection Pump Element	24000	8000	8000
Cylinder Head	60000	20000	8000

Table 3.2: Results for RUL and Next Overhaul of Wärtsilä 46F.

3.4.4 Electronic Systems

Life extension studies concerning control systems and telecommunication equipment can become very difficult, once creating a mathematical model to assess the remaining useful life of their components is time consuming and complex - many times there is even a lack of accuracy in the results. The objective of this analysis is to give an overview of both control systems and telecommunication equipment in a systematic and common way. As the analysis focus on high-level evaluations, a common framework defined specially for the electronic systems is developed, however not as a quantitative model.

An electronic system is roughly composed by hardware and software, that together process inputs and transform them into outputs. Hardware's are the physical pieces that when connected allow for the well functioning of the system, while software's are the computer programs that receive instructions, process them and allow the components to work. Figure 3.16 presents the definition used for the systems analysis.

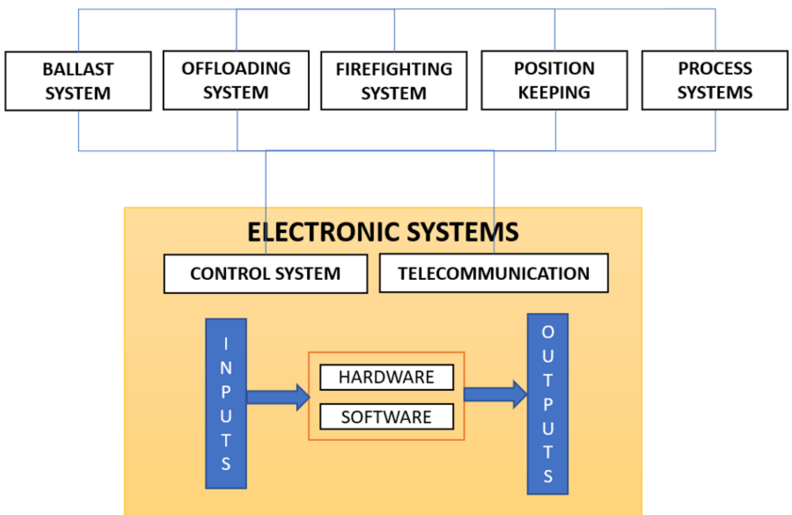


Figure 3.16: Telecommunication and Control as Electronic Systems.

The main control unit in the FPSO connects both marine and process control systems. Based on inputs from personnel at the company, it was seen that for a feasibility level study two types of analysis are made: 1) the current overall condition of the systems and 2) evaluations of condition, hardware and software during life extension period.

A computational tool is developed to gather all the information necessary. As it is mainly based on insights and opinion of experienced personnel, the life extension assessment should preferably be performed in a workshop with relevant people. During the workshop, the personnel are exposed to different categories of assessment and available options - they must decide upon one that best fits the problem being studied.

The life extension assessment is divide into 3 stages, which are treated individually in the next sections. Tables explaining the concepts for the defined options in each stage are available on Appendix A.4 - Electronic Systems, and a general overview is available on Figure 3.17.

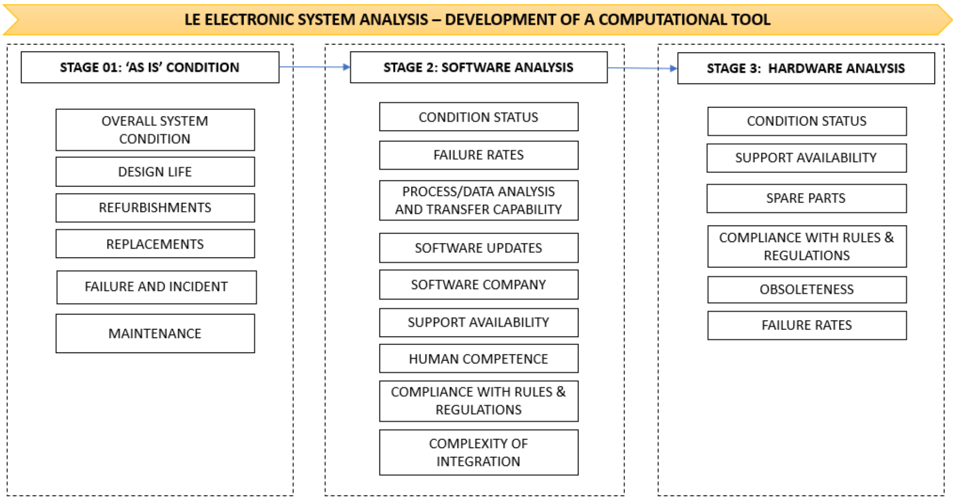


Figure 3.17: The Life Extension Analysis for Electronic Systems.

Stage 1: "As Is" Condition

"As Is" condition refers to the actual condition of the electronic systems, and it should reflect how the system is behaving at the time of assessment. It follows the same condition definitions as presented in Section 3.3, hence whether the system is good, bad, requires updates, has an average condition or if it is already obsolete should be selected. Another information needed is the initial design life of the electronic system, as after Stage 1 is completed, the management team will have an overview of the system's behaviour during its design life.

Refurbishing an electronic system is a very common approach - that is replacing parts of the entire system, restoring the operational reliability and increasing remaining useful life (Varde et al., 2014), hence condition assessment in FPSOs should also cover this set of parameters. Varde et al. (2014) states that a system can be refurbished due to a different reasons, such as age, defects, upgrades and obsolescence.

The big question concerning refurbishment is whether it is economical viable compared to a full system replacement (Varde et al., 2014). However, it must be understood that there is much more behind simply substituting systems entirely, as an electronic system interacts with different subsystems, and a full replacement or even refurbishment requires that those system are still integrated with each other.

Knowing if the system has already been refurbished or replaced gives a good overview of what can happen during the life extension period. If the information on what presented problems and when it was mitigated is provided, one can forecast better what may happen if the system's life is extended.

The last two inputs into the analysis are related to failures and maintenance. Failures and incidents are investigated in a system level, then it is required that the expert gives an overview of the percentages of components that have failed or had some kind of incident during regular operation. System condition is also highly influenced by maintenance, and thus a status on that is also required, following what was used before in Section 3.3. Figure 3.18 presents the analysis procedure for Stage 1 “As Is” Condition, and the full concepts for each information is available on Appendix A.4 - Electronic Systems.

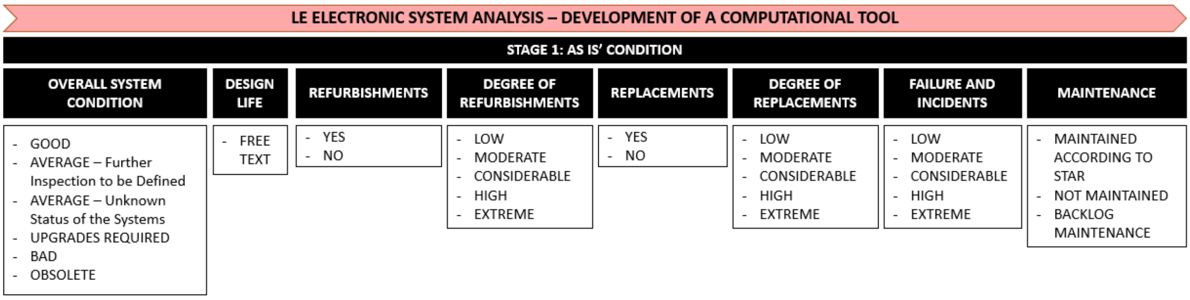


Figure 3.18: Life Extension Analysis Electronic Systems - Stage 1: “AS IS” Condition.

Stage 2: Software Analysis

The software life extension study starts by defining its current status - whether the software is working well, bad, is obsolete or has an average performance (meaning that the operator can experience analysis taking longer than usual or sudden stop of performance). Then, an estimation of failure rates is required and this can usually be found from reliability engineering documentation. When the information is not known, the analysis should rely in the experience of operator to choose among the failure rates options. The capacity of processing and transferring data and its complexity is also studied, as it is important to understand how much information is being exchanged between the systems.

The forecast into life extension period is performed by deciding upon five different parameters that give an overview if general support to the electronic system will be available or not. Availability of software updates, work force from the manufactures, specific support and human competence are among the criterion. The software analysis finishes by predicting if it will be possible to be compliant with rules and regulations, Figure 3.19 presents the proposed framework, and the full concept definition is available on Appendix A.4 - Electronic Systems.

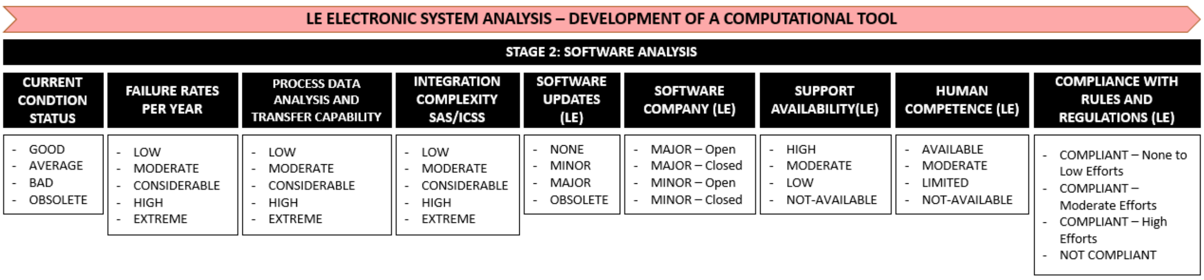


Figure 3.19: LE Analysis Electronic Systems - Stage 2: Software Condition.

Stage 3: Hardware Analysis

The hardware’s are the physical pieces that integrate the electronic systems. It can include transmitters, switchers, processors, actuators, and more.

The current condition of each piece is evaluated, as well as failure rates per year and support availability - using the same definitions as used for Stage 2: Software Analysis. It is also necessary to identify if there will be spare parts for replacing parts of the system or if the hardware will be obsolete. The analysis closes by assessing compliance. The outputs from all three stages will be used to guide decision makers whether the asset is a fit for life extension or not, due to the extension of work required to attain compliance. Figure 3.20 summarizes the analysis and the full concepts defined are available on Appendix A.4 - Electronic Systems.

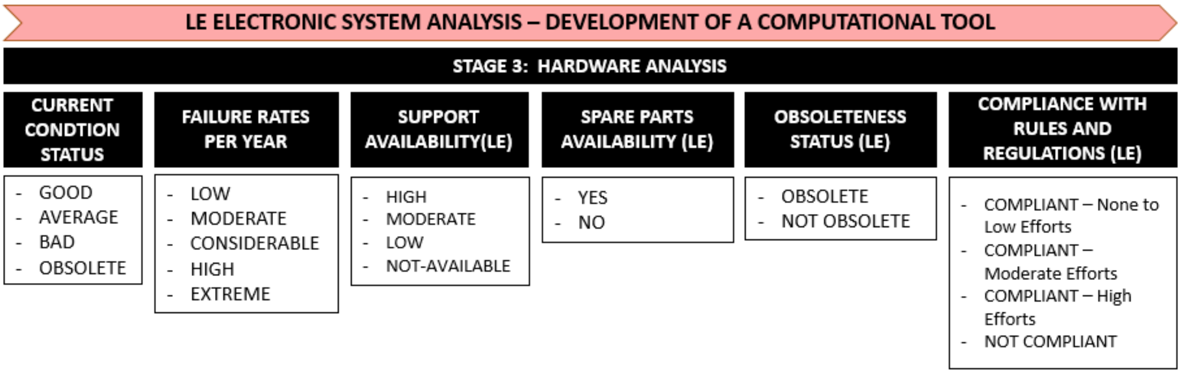


Figure 3.20: Life Extension Analysis Electronic Systems - Stage 3: Hardware Life Extension Analysis.

3.5 Phase 4: Risk Analysis and Risk Mitigation

The fourth phase in the methodology is the risk analysis and risk mitigation's, as presented on Figure 3.1. The risk analysis process is based on the development of a FMEA, adapted to the life extension assessment. It is performed in a systematic way for each of the systems being evaluated. Figure 3.21 presents the risk analysis framework, which is divided into 4 stages and developed into a worksheet.

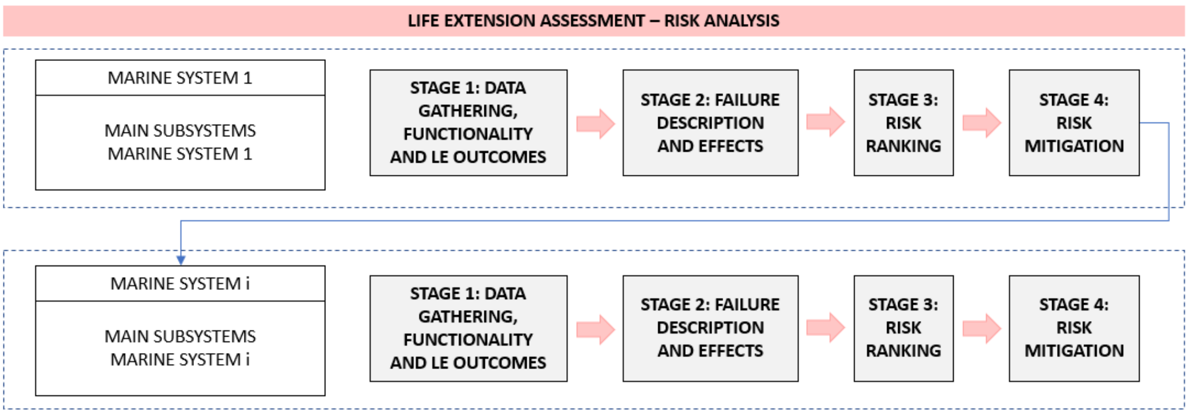


Figure 3.21: Stage 4: Risk Mitigation

The 4 stages stages of the risk analysis are: data gathering, failure description and effects, risk ranking and risk mitigation actions. The following sections describe each process and what are the expected outcomes that are be addressed in decision making process.

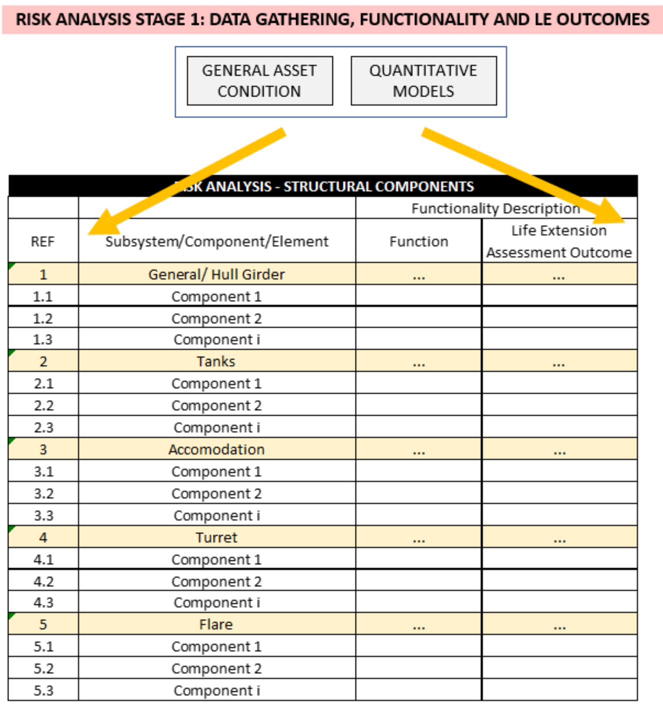
The risk analysis can get very broad if one is to study each possible hazards and consequences. Hence, the procedure should focus on the worst case scenario, therefore focusing on one outcome for each of the many systems being evaluated.

3.5.1 Stage 1: Data Gathering, Functionality and Life Extension Outcomes

The first step consists in organizing the information defined before. From the condition assessment, it is important to do a screening and identify which components belong to the subsystem being analysed. Again, a high level assessment should be made, hence looking only for the main information.

For instance, if the subsystem "Hull Girder" was being assessed, the first step would be identifying which information gathered in the past sections are belonging to this group. This could include the RUL information on the girder plates and stiffeners, the general external and internal coating status, the main deck condition and so on. The same process is performed to the next subsystem, until all the required information is gathered.

Then, as required by the FMEA tool, the functions of all parameters gathered should be identified. It was decided to create a column to fill in the outcomes of the life extension assessment in a summarized manner, as this can facilitate the failure analysis. Once the data is organized and well structured, it is easier to decide upon a final outcome of life extension work and to go back into the required information whenever needed. Figure 3.22 presents an overview of how the process could look like, as it varies according to what marine systems is being analysed.



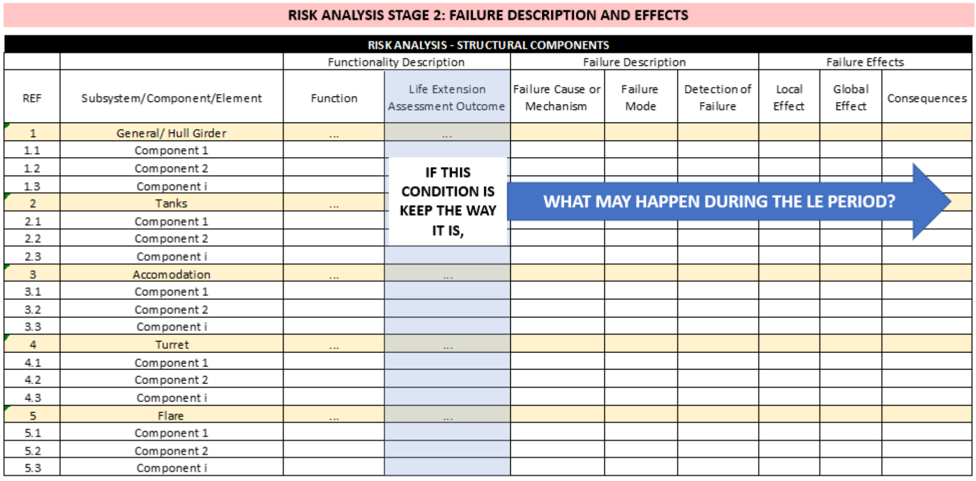
		Functionality Description	
REF	Subsystem/Component/Element	Function	Life Extension Assessment Outcome
1	General/ Hull Girder	...	...
1.1	Component 1		
1.2	Component 2		
1.3	Component i		
2	Tanks	...	...
2.1	Component 1		
2.2	Component 2		
2.3	Component i		
3	Accomodation	...	...
3.1	Component 1		
3.2	Component 2		
3.3	Component i		
4	Turret	...	...
4.1	Component 1		
4.2	Component 2		
4.3	Component i		
5	Flare	...	...
5.1	Component 1		
5.2	Component 2		
5.3	Component i		

Figure 3.22: Stage 1: Data Gathering, Functionality and Life Extension Outcome.

3.5.2 Stage 2: Failure Description and Effects

The analysis proceeds by identifying the possible failures and effects from the outcomes of the life extension assessment. Here, the mindset is forecasting what would happen to the unit if the current condition is kept.

The failure causes and mechanisms should be identified, as well as failures modes and how it can be detected. Then, the failures effects are determined by local and global effects, as well as consequences. This assessment can grow exponentially because the same failure cause can have a wide range of consequences. Hence, it is necessary to keep the assessment to as little as possible, always keeping in mind the mindset defined before. Figure 3.23 presents a proposed worksheet for the second stage of risk analysis.



RISK ANALYSIS STAGE 2: FAILURE DESCRIPTION AND EFFECTS

RISK ANALYSIS - STRUCTURAL COMPONENTS

		Functionality Description		Failure Description			Failure Effects		
REF	Subsystem/Component/Element	Function	Life Extension Assessment Outcome	Failure Cause or Mechanism	Failure Mode	Detection of Failure	Local Effect	Global Effect	Consequences
1	General/ Hull Girder	...	...						
1.1	Component 1								
1.2	Component 2								
1.3	Component i								
2	Tanks	...							
2.1	Component 1								
2.2	Component 2								
2.3	Component i								
3	Accomodation	...	...						
3.1	Component 1								
3.2	Component 2								
3.3	Component i								
4	Turret	...	...						
4.1	Component 1								
4.2	Component 2								
4.3	Component i								
5	Flare	...	...						
5.1	Component 1								
5.2	Component 2								
5.3	Component i								

Figure 3.23: Stage 2: Failure Description and Effects.

3.5.3 Stage 3: Risk Ranking Process

The third stage is performed by ranking all the hazards identified before - it consists of giving a value of likelihood and severity for each consequence. The proposed matrix, based on ISO 17776 1999 (Paik & Thayamballi, 2007) and feedback from personnel at the company, is presented in Table 3.3.

NEGLIGIBLE		LIKELIHOOD				
ALARP		1	2	3	4	5
INTOLERABLE		Very Unlikely	Unlikely	Possible	Likely	Very Likely
SEVERITY		Less than 1%	1- 15%	15 - 40%	50 - 60%	60% +
1	Insignificant	1	2	3	4	5
2	Minor	2	4	6	8	10
3	Moderate	3	6	9	12	15
4	Major	4	8	12	16	20
5	Catastrophic	5	10	15	20	25

Table 3.3: Stage 3: Risk Matrix and Risk Ranking

The likelihood is divided into five categories, from very unlikely to very likely, and some percentages are also proposed to guide the assessment. The severity are ranked from insignificant to catastrophic, and can be applied to a different set of risk categories that are defined in Table 3.4.

OTHER RISK CATEGORIES		HUMAN SAFETY	ENVIRONMENT	REPUTATION	ASSET	OPERATION
1	**Insignificant**	Slight Injury	Slight Pollution Effects	Slight Impact	Slight Damage	No Shutdown
2	**Minor**	Minor Injury	Minor Pollution Effects	Limited Impact	Minor Damage	Shutdown for a few hours
3	**Moderate**	Major Injury	Local Pollution Effects	Considerable Impact	Local Damage	Shutdown for a few weeks
4	**Major**	Single Fatality	Major Pollution Effects	Major Impact	Major Damage	Shutdown for a couple of months
5	**Catatrosphic**	Multiple Fatalities	Massive Pollution Effects	Major International Impact	Extensive Damage	Permanent Shutdown

Table 3.4: Stage 3: Risk Categories and Severity

The risk is calculated by multiplying likelihood and severity, and is categorized into three areas: negligible, ALARP (As Low as Resonable Practical) and intolerable. All the risks that sit into negligible area do not need further assessment, while the ones in ALARP and intolerable areas need. In the ALARP region, each consequence should be assessed individually to understand if it a mitigation action is necessary. Intolerable risk are usually not accepted and must always be mitigated.

3.5.4 Stage 4: Risk Mitigation

From the results of risk ranking, the fourth step can be carried out. Like stated before, mitigation actions should be proposed for all the risk in intolerable areas, and whenever decided to be effective into the ALARP ones.

As an example, one can consider that the outcome of the life extension assessment is that some plates and stiffeners from the hull girder have a remaining life shorter than the life extension period. This could result into a catastrophic failure, with the hull loosing strength and collapsing. After ranking the hazards, it was seen that it resulted in an intolerable risk, and therefore mitigation actions should be proposed.

A solution could be reinforcing all the plates and stiffeners that presented shorter remaining life. Then, the effects of this procedure are to be assessed by performing a new risk ranking, i.e. defining a new value of likelihood and severity but now considering that no component has a lower life value than the life extension period. For this analysis, at least the likelihood of the catastrophic failure happening should be decreased, what would also decrease the final risk. Figure 3.24 gives a general overview of how the procedure should look like after the all the stages are finalized.

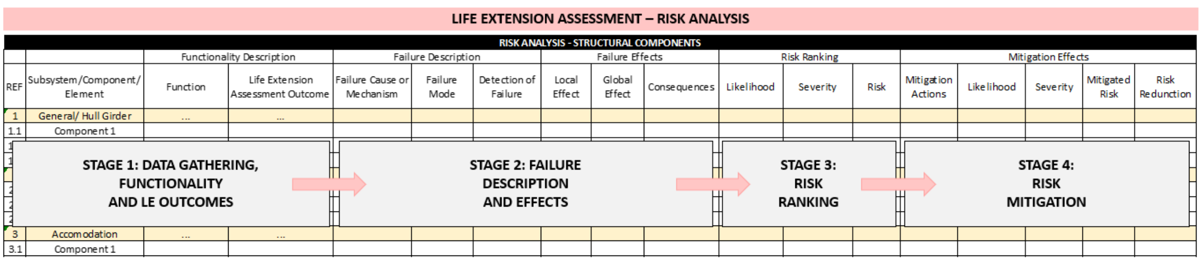


Figure 3.24: Overview of Risk Analysis and Risk Mitigation.

3.6 Phase 5 and 6: Scope of Work, Work packs and Cost Analysis

Phases 5 and 6 gather all the outcomes from the previous analysis and transform them into a scope of work. Here, the mindset is to understand what work is necessary in order to obtain compliance and to get authorized to operate for longer, as well as regular life extension work. Work packs, which are documents that fully describe what type of work is necessary to fully achieve a determined condition should be created and costed.

The work packs can include simple painting scope of work, to inspections and surveys so that a condition can be improved. Depending on the scope of work, it is required to know the dimensions and components of each system to calculate material and man-hours required.

For this master thesis, whenever possible the relevant work packs are costed based on Butler (2012), who proposed different methods to estimate man-hours for ship repair. Thus, to define a total for the scope of work, a rate in USD/man-hours must be used.

3.7 Phase 7: Economical Feasibility Analysis

The decision on whether the life extension project is viable or not is performed by an economical feasibility analysis. Here, decision makers must decide upon a total cost for the project (CAPEX), evaluate whether the unit could be chartered for longer and compare it with a sale value (sale for scrap or for another shipowner).

Some of the parameters that can influence the analysis are the oil price, the charter rate, steel weight, financing options, work required and much more. In principal, the unit is decided to be a fit if the profit during the life extension period is higher than defined percentage over the value of sale.

This phase varies depending on the vessel and information available. Hence, there is no fixed proposed framework to perform it. How the economical feasibility analysis was performed while testing out a fictional asset for this master thesis is presented in Chapter 5. It includes assessing oil prices, determining profit margins and comparing the forecasted values into selling the unit for scrap.

Chapter 4

FPSO and its Marine Systems - A Mock Up based on Real Life Scenario

This chapter describes a FPSO, its marine systems and an oil field that are later used to test out the methodology. It starts by characterizing an oil field and presenting some design requirements, followed by a procedure similar to conceptual ship design to characterize the vessel. Lastly, the marine systems identified before are described for further analysis. It is a mock up vessel with systems defined based on real life requirements and information available on literature.

4.1 Field Characteristic's and Design Requirements

In naval architecture, it is common to design the ship based on a set of requirements that comes from the shipowner. It includes the ship's mission, proposed route and even some restrictions considering size. An usual ship's mission is to transport cargo (payload) from point A to B, which gives insights to the design team that the ship must be able to carry a specified amount of load while having dimensions that allow it to dock safely into harbours A and B.

A FPSO, however, has a different mission - it needs to remain in place while producing, storing and offloading crude oil and gas. Usually, the shipowner wants a vessel that can operate in specific field, producing and offloading a determined amount of oil. Hence, the field characteristics, client requirements, regulatory compliance and class certification drive the design of the vessel.

A field definition is needed because it gives important information about the FPSO operation, such as if the environment is corrosive, with hot temperatures, in deep-water and so on. Other consideration to be made is about the location - harsh weathers or benign waters - as it affects the metaocean data to be used in the design phase.

This section presents the definition of an oil field, gathering the necessary information to later on propose a fictional asset to operate in it. The field is decided to be in Brazil, and with 15 years of current exploration.

4.1.1 The Oil Field

The oil field definition begins by selecting a geographical location where the field is situated - this assessment shall be made to a field located in the Brazilian Continental Shelf (BCS). The BCS is large and composed by 17 basins.

Campos basin is the largest explored region in the BCS. According to Petrobras (2013), it has an area of around 100.000 squared kilometers - from the Arraial do Cabo, in Rio de Janeiro State, to Vitória, in Espírito Santo State. The oil fields depths range from shallow waters, like the first oil field - Garopa - discovered in 1974 with 124m water depth (Petrobras, 2013), to Marlim field in deep waters of up to 1.100m (de Oliveira & Coelho, 1989).

Santos basin extends from Cabo frio, in Rio de Janeiro State, to the south of Brazil in Florianopólis, in Santa Catarina State, with an area of over 350.000 squared kilometers (Petrobras, 2010). It is also where the biggest chunk of the Brazilian pre-salt layer is located, turning it into a very attractive opportunity with the largest area for exploration (Silveira de Souza & Chaves Sgarbi, 2019). According to Silveira de Souza & Chaves Sgarbi (2019), the proximity to Campos basin is also a contributing factor for Santos basin becoming attractive for investment. As stated before, Campos basin is the most explored region in Brazil with the complete infrastructure for exploration already available - Santos basin being next to it reduces the costs for required infrastructure (Silveira de Souza & Chaves Sgarbi, 2019).

Once the objective of the thesis is to test out a FPSO that has already been operating for a certain period, it was decided to perform the analysis for a fictional field that gathers information from different existing fields. This was done because the technical information on oil fields is not of easy access. Hence, the selection criteria was basically a benchmark online, and whenever suitable data was available it was selected.

One of the fields chosen was Marlim Sul which is the fifth largest field in Brazil (G1, 2018). Marlim Sul has been in operation since 1994 and back in 2018, ANP (Agência Nacional do Petróleo), extended its operations until 2052. The information provided by ANP in resolution number 396/2018 is used to define some of the field characteristics (ANP, 2018). The field has a water depth of 1400 m and an area of 884,11 km^2. An illustration of its geographical position can be seen in Figure 4.1

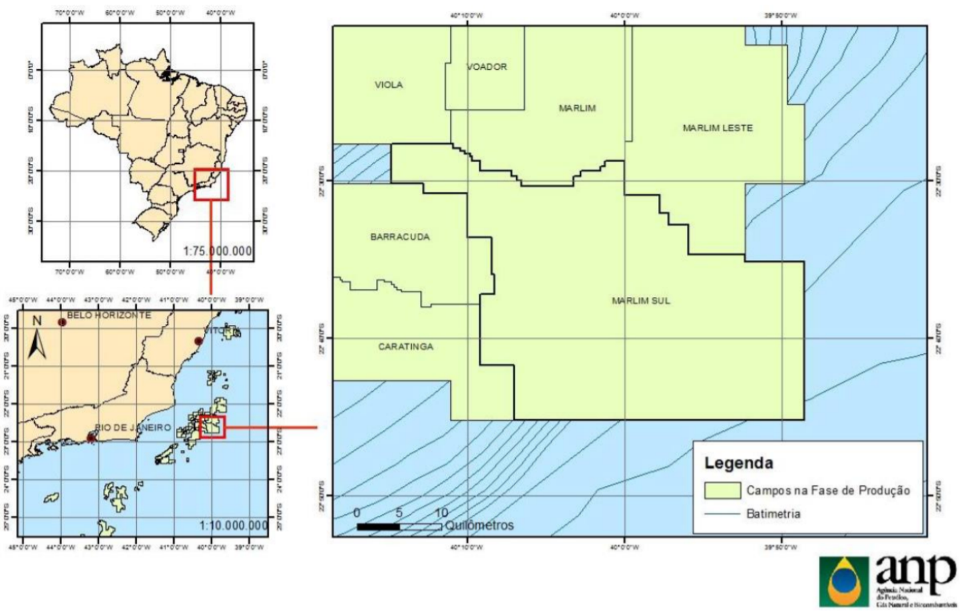


Figure 4.1: The Marlim Sul Location (ANP, 2018).

The field's API (American Petroleum Institute Gravity) vary from 13 deg to 29 deg, and as in 2017 had a volumes "in place" of over 8.000 $MBBLS$ of oil and 120.000 Mm^3 of natural gas. For this assessment, an API of 20 was chosen, what defines the reserves as heavy oil. In 2017, Petrobras announced that oil was found in the pre-salt region of Marlim Sul field (Petrobras, 2017). For this case study, it is assumed that the life extension period is to be performed for operation in the pre-salt region.

Other source of information used was the document"Brazilian Oil and Gas Report 2018/2019 - Trends and Recent Development" developed by EPE (Empresa de Pesquisa Energética), which is a government entity attached to the Ministry of Mines and Energy (EPE, 2018). EPE suggests that most pre-salt fields have high GOR (gas to oil ratio) (EPE, 2018), hence a value of GOR = 80 is assumed for the thesis analysis, also considering heavy oil type (Bruhn et al., 2003).

EPE reports also gives an overview of the typical C02 levels for Campos and Santos basins - presented in Figure 4.2. Considering the location of Marlim Sul field, a value of CO_2 = 0.5 was chosen for the assessment. The outcome of the benchmark is presented in Table 4.1.

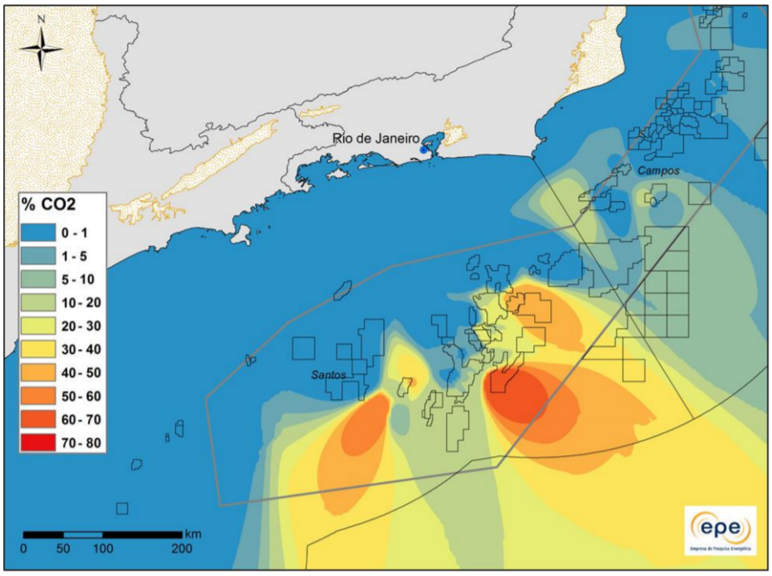


Figure 4.2: C02 concentrations in Campos and Santos Basins (EPE, 2018).

Oil Field Characteristics		
Water Depth	1400	m
Area	884.11	km^2
Oil Reserves	8000	MBBLS
Gas Reserves	1200000	Msm^3
API	20	deg
Oil Type	Heavy Oil	
GOR	80	
CO2 %	0.5	

Table 4.1: Oil Field Characteristics for the Assessment.

The production profile of the field is also fundamental, and this thesis presents only the one related to oil. The profile is based on a typical reservoir profile available on Kemp (2015) and Figure 4.3 presents two sets of information: the original profile and the actual profile. For this fictional assessment, the original refers to that used when the field started to be studied and the FPSO begun to be designed. It can be seen that a decline in production would start at around 2009, ceasing production totally in 2030.

However, as the works developed a new well was connected to the production, becoming more optimistic than before. It can be seen that there is a higher production rate and that the field ceases production in 2045. With this, a life extension assessment is justifiable.

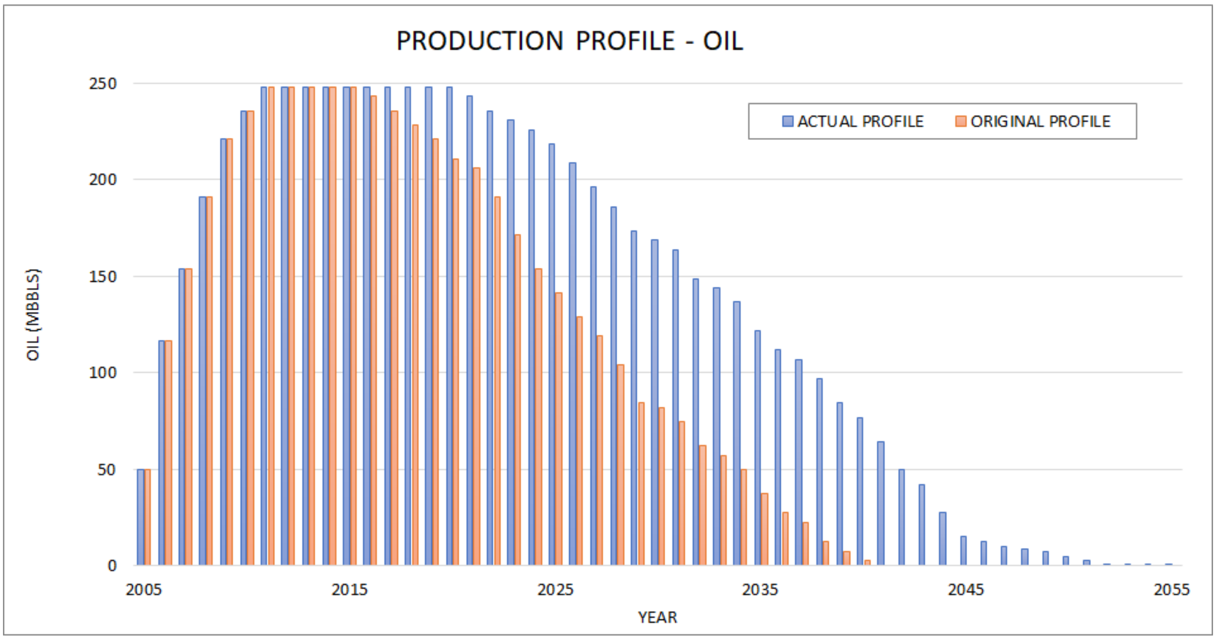


Figure 4.3: The Field Oil Production Profile.

The metaocean conditions around the field's region are presented on Table 4.2. Using Campos basin as reference, the necessary information was extracted from the book "Offshore Structures: Volume I: Conceptual Design and Hydromechanics" (Clauss et al., 2014).

Campos Basin Metaocean Data		
100 Year Extreme Design Wave		
Max Wave Height	8.4	m
Related Period	11	s
Extreme Current		
Surface	2.5	m/s
Bottom	1	m/s
Extreme Wind	46	m/s

Table 4.2: Campos Basin Metaocean Data (Clauss et al., 2014).

The last set of information needed before designing the FPSO are the asset requirements. Analysing the FPSOs located in both Santos and Campos basins, it was concluded that the unit should present the characteristics available on Table 4.3. The next sections presents the steps taken to perform a simple conceptual design of the unit.

FPSO Design Requirements		
Storage Capacity	1000000	BBLS
Oil Production Capacity	170000	BOPD
Gas Handling Capacity	10	m^3/d
Water Injection Capacity	60000	m^3/d
Produced Water Capacity	25000	m^3/d

Table 4.3: FPSO Design Requirements.

4.2 FPSO Description

This section presents the steps on defining a mock up FPSO to later on test out the life extension methodology proposed. The resulting FPSO and marine systems are a combination of concept design procedures and information available in books and online.

The main dimensions, for instance, were define by regression analysis, while the general arrangement and structural drawings are available in the book “Ship Shaped Offshore Installations” by Paik & Thayamballi (2007).

Designing the FPSO entirely would be time consuming and not possible due to the limited time of the master thesis. Hence, as the objective is to test out a methodology in an existing FPSO, a combination of different information was selected as the best option, and whenever applicable ship design concepts were used.

4.2.1 Determining the Main Dimensions and Mooring Selection

Intending to determine the main dimensions of the unit, a regression analysis is proposed. A database was created, gathering information of FPSOs available online in sources like Marine Traffic, shipowners websites and in Ha et al. (2017). The complete regression analysis plots are available on Appendix B.1 - Regression Analysis.

To determine the length of the unit, the storage capacity was used as the regression factor. The analysis can be seen in Figure 4.4- it resulted in a unit with L_{OA} = 312.7 m. The breadth, draft and depth dimensions were determined based on the ratios L/B, B/D, T/D and B/T. The Block Coefficient value, C_B, was also found by the regression analysis, as presented in Figure 4.5. The main dimensions of the FPSO are summarized in Table 4.4.

Storage Capacity	1000000	BBLS
Dimension Ratios		
L/B	6.03	
B/T	2.70	
B/D	1.98	
T/D	0.67	
FPSO Dimensions		
L	312.7	m
B	51.8	m
T	19.2	m
D	26.2	m
C_B	0.76	
∇	235712.3	m^3

Table 4.4: FPSO Dimensions and Ratios.

The type of mooring system solution was decided based on a benchmark with other units operating in Campos and Santos basin. It was seen that most FPSOs had spread mooring as their mooring solution. Hence, the same configuration was decided for this FPSO.

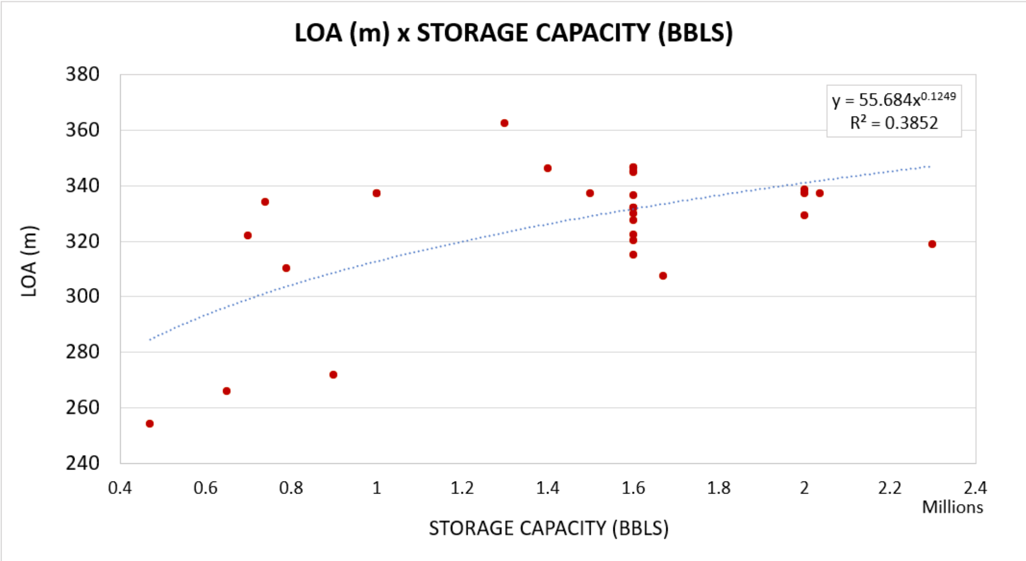


Figure 4.4: Regression Analysis to Determine L_{OA}.

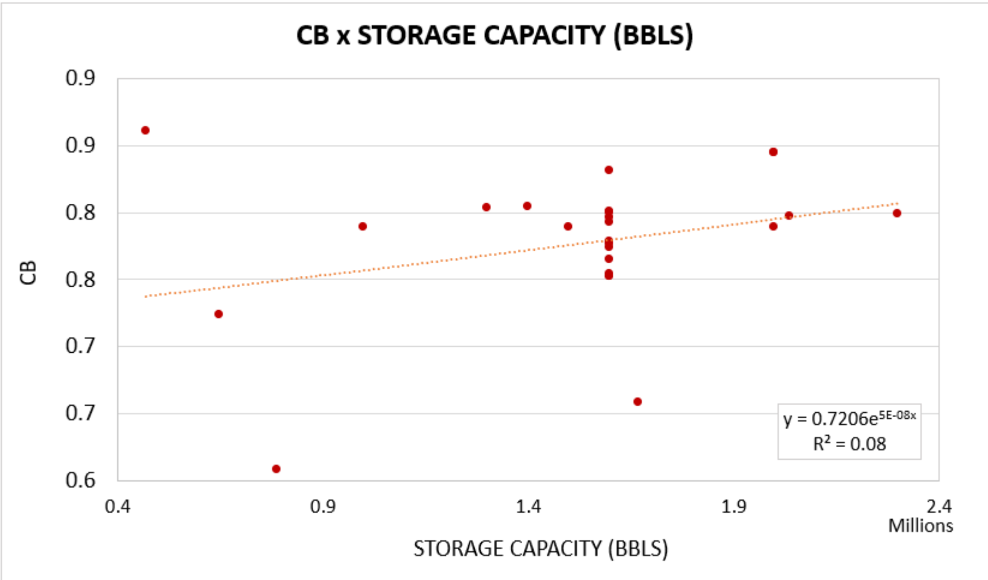


Figure 4.5: Regression Analysis to Determine C_B.

4.2.2 Hull General Arrangement

The hull general arrangement to be used is the one presented by Paik & Thayamballi (2007), in the book "Ship Shaped Offshore Structures". Although the unit has a larger cargo capacity than the FPSO described for the master thesis, they both have similar dimensions and the mooring solution is also the same - spread mooring.

Once again stressing that the goal is to test out the life extension methodology and not the to design a FPSO, this is considered acceptable. Figure 4.6 presents the general arrangement selected.

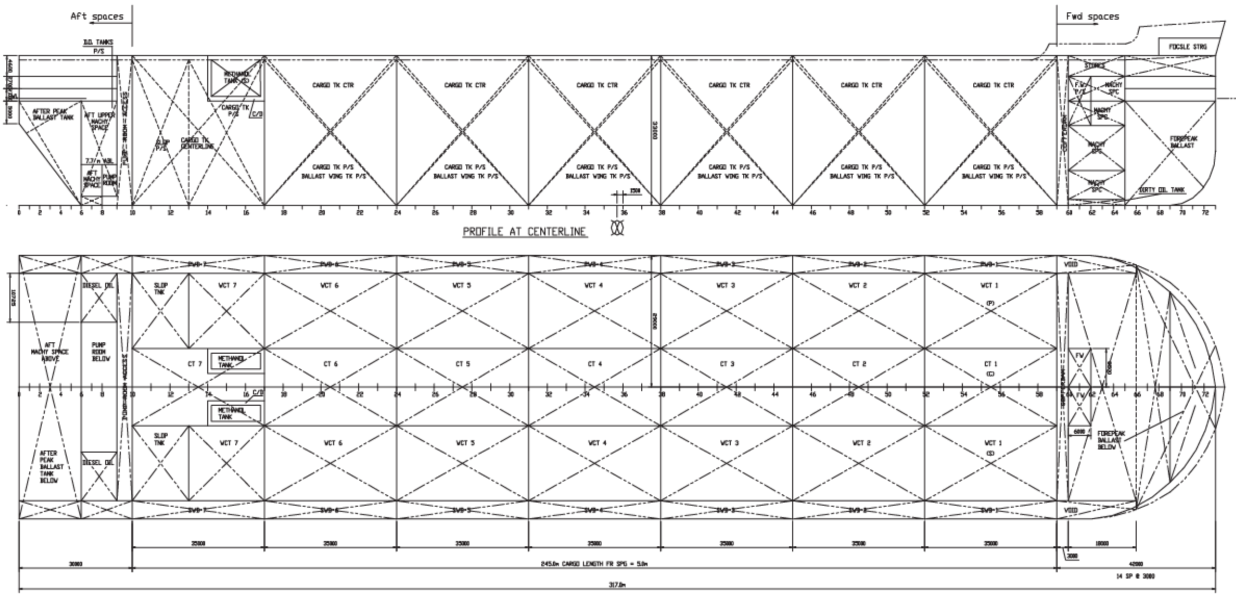


Figure 4.6: The Hull General Arrangement (Paik & Thayamballi, 2007).

4.2.3 Structural Design

The same model presented in section 4.2.2 by Paik & Thayamballi (2007) is used for scantlings and structural drawings. This unit has ballast tanks at the sides, and 3 groups of cargo tanks. The author presented the thickness values for both longitudinal and transverse elements from stiffeners and plates, what is considered valuable for testing the methodology. A complete structural arrangement for the midship section can be found in Appendix A.1, while Figure 4.7 presents a simplified visualization.

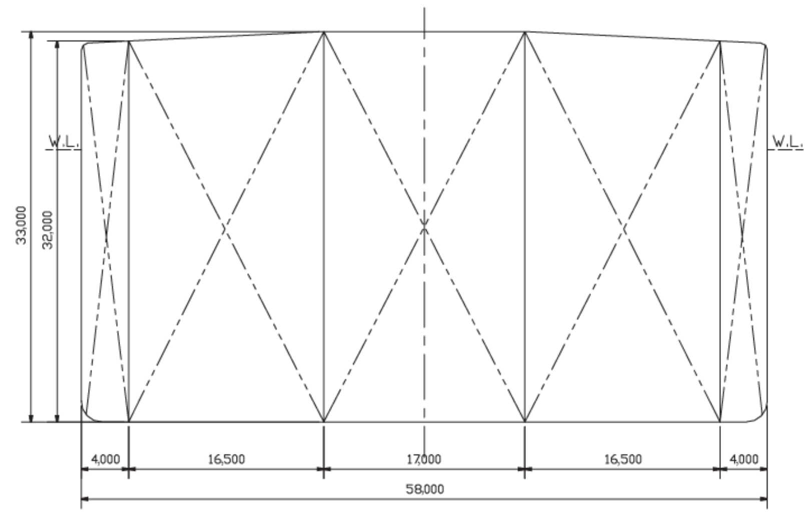


Figure 4.7: The FPSO Midship Section (Paik & Thayamballi, 2007).

4.2.4 3D Hull Model

The 3D model of the hull was generated by using a pre-existing model in the open source software Free-ship. An initial model with hull lines that resembled a FPSO was chosen, and then scaling and parametric transformations were applied until the main dimensions and vessel's C_B similar to the requirements were found.

The model was exported as an IGES surface, and the software Rhino 3D was used to perform the remaining 3D modelling. The modelling process was done during the trial time of Rhino 3D, hence no license was required. Figure 4.8 presents the general overview of the FPSO hull - with topside modules. The only objective of this model is to be illustrative and guide the decisions when describing the main marine systems, as well as facilitating possible area and volumes calculations.

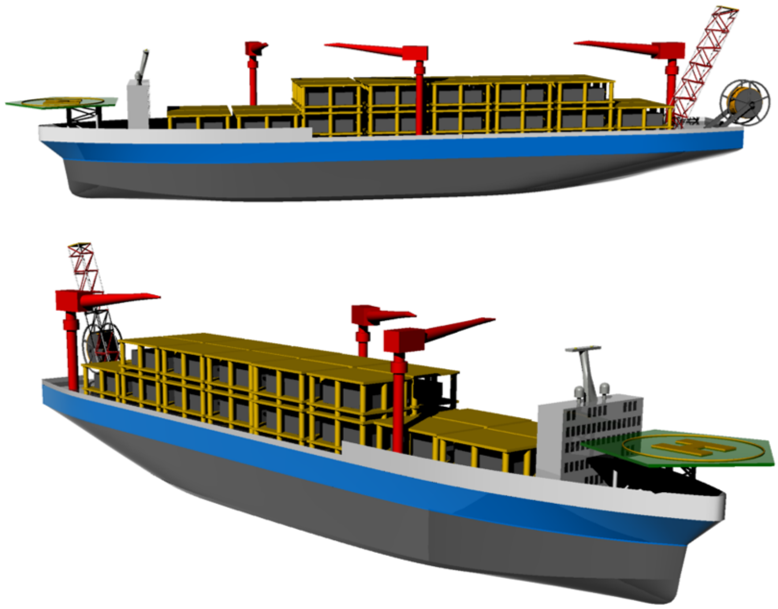


Figure 4.8: An Illustration of how the FPSO could look like.

4.3 FPSO Main Marine Systems

This section describes the remaining FPSO marine systems - power generation, firefighting system, offloading system and control and telecommunication systems.

4.3.1 Main Power Generation

The power estimation in the FPSO differs from the typical merchant ship, that considers mostly the required power for propulsion, hotel loads and other essential ship systems. During the FPSO power estimation, the design team must consider not only the required power for the marine systems, but also the process facilities.

The field characteristic's also drastically influence the power consumption of the FPSO modules, as depending on the oil characteristics it might need more or less power to perform the essential production functions. For this master thesis, it is not essential to know exactly how much the asset would consume, but it is needed to have a description of the power generation systems. This includes defining the quantity of turbines, generators and engines, and the basic power output. With this information known, it is possible to select a vendor and find the necessary data on overhauls.

A research was made into available articles and it was decided to use the information provided by Bang (2002), Le Cotty & Selhorst (2003), da Costa Filho (2005) and Brandão et al. (2006). The authors provided information into FPSO design and an overall power consumption to the units. da Costa Filho

(2005) provides useful information on P-43 and P-48, both Petrobras FPSO's operating in Campos basin - just like the fictional asset defined for the life extension assessment.

Although one cannot assume that fields in the same basin would have similar process requirements, using the arrangement described by da Costa Filho (2005) is considered acceptable for the objective of this master thesis. From the data provided by da Costa Filho (2005), it was seen that the fictional asset and base models had different volume rates for the process systems, but same storage capacity. All the process parameters affect the required power in the unit, therefore a proportion factor was calculated from the values of P-43/P-48 to the ones related to the unit. Then, a simple average was found and this factor was used as the main proportion factor for the power requirement. The fictional asset needs to be supplied with 96 MW.

FPSO	Petrobras P-43 /P-48	Fictional Asset	Proportion (FA/P)
Loa (m)	337.05	312.70	0.928
B (m)	54.54	51.80	0.950
T (m)	21.07	19.20	0.911
D (m)	27.00	26.20	0.970
Topside Weight (ton)	14000	13780	0.984
Storage Capacity (BBLS)	1000000	1000000	1.000
Oil Production Rate (m3/d)	24000	27027.84	1.126
Gas Compression Rate (Mm3/d)	6	8	1.333
Produced Water Rate (m3/d)	20000	18000	0.900
Water Injection Rate (m3/d)	40000	32000	0.800
Power Requirement (MW)	92	96	1.040

Table 4.5: Determining the Fictional FPSO Required Power based on Petrobras P-43/P-48.

According to da Costa Filho (2005), P-43/P-48 main power generation systems are supplied with 4 dual-fuel turbo-generators of 28750 kVA each, and during normal operations only 3 are used. For the emergency generation systems, there are 2 diesel generators that provide 1875 kVA.

Main Power Equipment

Wärtsilä was selected as the provider to the asset power system due to the great availability of information online. The dual-fuel Wärtsilä 46DF, engine type 16V46DF that provides 18.320 kW is selected-hence, 6 engines are needed returning a total of 109.92 MW, plus 2 more that are used for redundancy. All the technical information for Wärtsilä 46DF/16V46DF can be found in the supplier's website. For the emergency power generation, it was decided upon a value of at least 5 MW, supplied by 3 diesel-engines Wärtsilä 20/8L20. Figure B.7 presents is an illustration of both engines, and they should use heavy fuel.

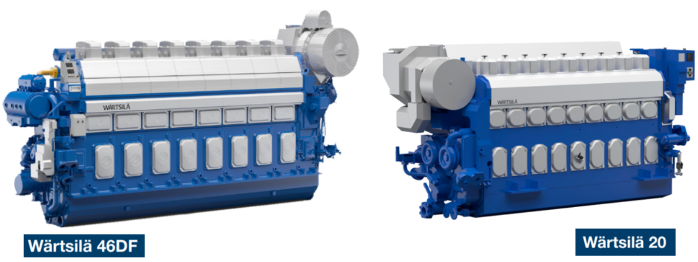


Figure 4.9: Wärtsilä 20 and Wärtsilä 46DF (Wärtsilä, 2019).

In order to facilitate the assessment, no other components (pumps, turbines and generators) are going to be considered separately. Instead, only the ones listed by Wärtsilä 46DF and Wärtsilä 20 shall be considered. The overhauls and replacement periods are available on Appendix B.3 - Overhauls and Replacements.

Distribution Systems - Pipes

The distribution system pipes sizes are defined based on available information of Schedule 40 pipes from Pipefit (2020) and are presented on Table 4.6.

Power Generation			
Location	Piping Group ID	d (mm)	t (mm)
Fuel Transfer System	CPG 1	114.30	6.02
Fuel Transfer System	CPG 2	219.10	8.18

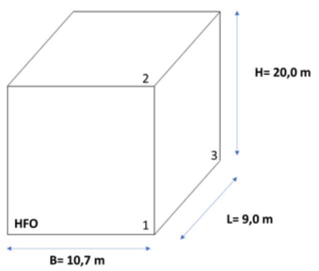
Table 4.6: Fuel Transfer System Piping Characteristics.

Fuel Tank

In merchant ship design, the size of fuel tanks is estimated based on engine daily fuel consumption and how long the vessel must sail without refuelling. As a rough estimation for the fictional FPSO, an oil taker is used as basis. The total volume was calculated based on information available by Levander (2012), that presents data on a 285m long tanker. This unit carries 3549 ton of fuel, what would give a volume of 3513.9 m^3 assuming a density of 1010 kg/m^3. Simply extending this value to the size of the FPSO, a volume of approximately 3855 m^3 was found.

The fuel tank dimensions are estimated according to the general arrangement presented on Figure 4.6, where there are two fuel tanks, with a total breadth of 10725 mm each. The length is estimated to be around 9000 mm, and each tank shall have a total volume of 1927.9 m^3. Hence, the total height is 20000 mm for each one.

The fabrication characteristics - i.e. the plate and stiffeners thickness - are considered the same as for the cargo tanks presented in the midship section in Appendix A.1 - Structural Arrangement. No data was found about transverse bulkheads, so the same values as longitudinal's were selected. Once the proposed quantitative model to forecast corrosion effects only requires the lowest thickness value of each element, only two values of thickness are presented: the lowest plate thickness and the lowest stiffener thickness for the fuel tank. Figure 4.10 presents the main characteristics of one fuel tank, along with the fabrication parameters.



2X TANKS of 1927.2 m3 with HFO

Faces	Plate t_min (mm)	Stiffener t_min (mm)
1 (Transverse Bulkhead)	17.50	12.00
2 (Deck Shell)	30.00	15.00
3 (Longitudinal/Side Shell Cargo)	17.50	12.00
4 (Bottom Shell)	31.00	15.00
5 (Transverse Bulkhead)	17.50	12.00
6 (Longitudinal/Side Shell Cargo)	17.50	12.00

Figure 4.10: Fuel Tank Characteristic's.

4.3.2 Firefighting System

Framo is the chosen manufacturer for the fire fighting pumps with the Diesel-Electric Fire Water pump system (Framo, 2020). According to the manufacturer, it is a self-contained system that includes all necessary auxiliary systems.

It is composed by a submerged electric fire water pump, a surge damping tank, air evacuation system, and fire water pump container with many main components (diesel engine, generator, oil circulation unit, HVAC, fuel oil tank, ...) (Framo, 2020). An illustration of the system can be seen in Figure 4.11. For this assessment, as only marine systems are considered, the fire fighting system should consider the machinery area, accommodation and control room.

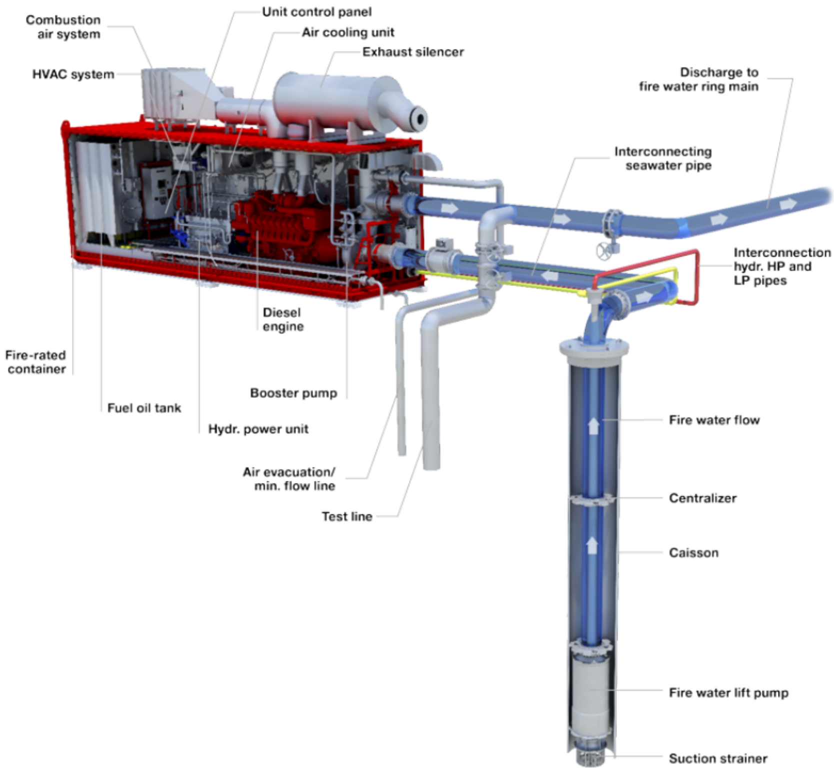


Figure 4.11: Framo's Firefighting System (Framo, 2020).

Distribution and Deluge System

A typical deluge system for a FPSO would include valves, pipes, sprinkles, fire detection systems, pumps, pipes, water tanks and so on. Once again, schedule 40 from Pipefit (2020) are selected and presented on the Table below.

Location	Piping Group ID	d (mm)	t (mm)	c (mm)
Accommodation	APG 1	73.00	5.16	3.00
Accommodation	APG 2	88.90	5.49	3.00
Accommodation	APG 3	101.60	5.70	3.00
Machinery Room	MRPG 1	88.90	5.49	3.00
Machinery Room	MRPG 2	101.60	5.70	3.00
Machinery Room	MRPG 3	114.30	6.02	3.00
Machinery Room	MRPG 4	141.40	6.55	3.00
Control Room	CRP G1	73.00	5.16	3.00
Control Room	CRP G2	88.90	5.49	3.00

Table 4.7: Firefighting System Piping Characteristics.

Pumps

As seen previously, Framo's submerged electric pumps is the one used for the firefighting system. According to the manufacturer, it is "a close-coupled, end-suction centrifugal pump with one or two stages, driven by an integrated oil-filled induction motor" (Framo, 2020). From information available at the manufacturer's website, it was decided to choose SH 300 with powered by a diesel engine with a tank to supply it for 18 hours.

4.3.3 Offloading System

Two main types of offloading process can take place in a FPSO - exporting to a shuttle tanker or to land by pipelines (Paik & Thayamballi, 2007). During the design phase, the offloading system requirements and configurations are based not only in the storage capacity of the unit but also in parameters from the shuttle tanker (or pipelines if that is the case). It is necessary to design a system that considers time and frequency of offloading, so that the process is profitable. For this fictional FPSO, the shuttle tanker is selected and is to be performed by the Tandem method.

Considering the FPSO offloading systems itself, it is composed by the hoses, tanks, pumps and distribution - each with its subsystems. One manufacture that provides solutions for the oil and gas industry is Eureka, and a typical cargo offloading system can be seen in Figure 4.12.

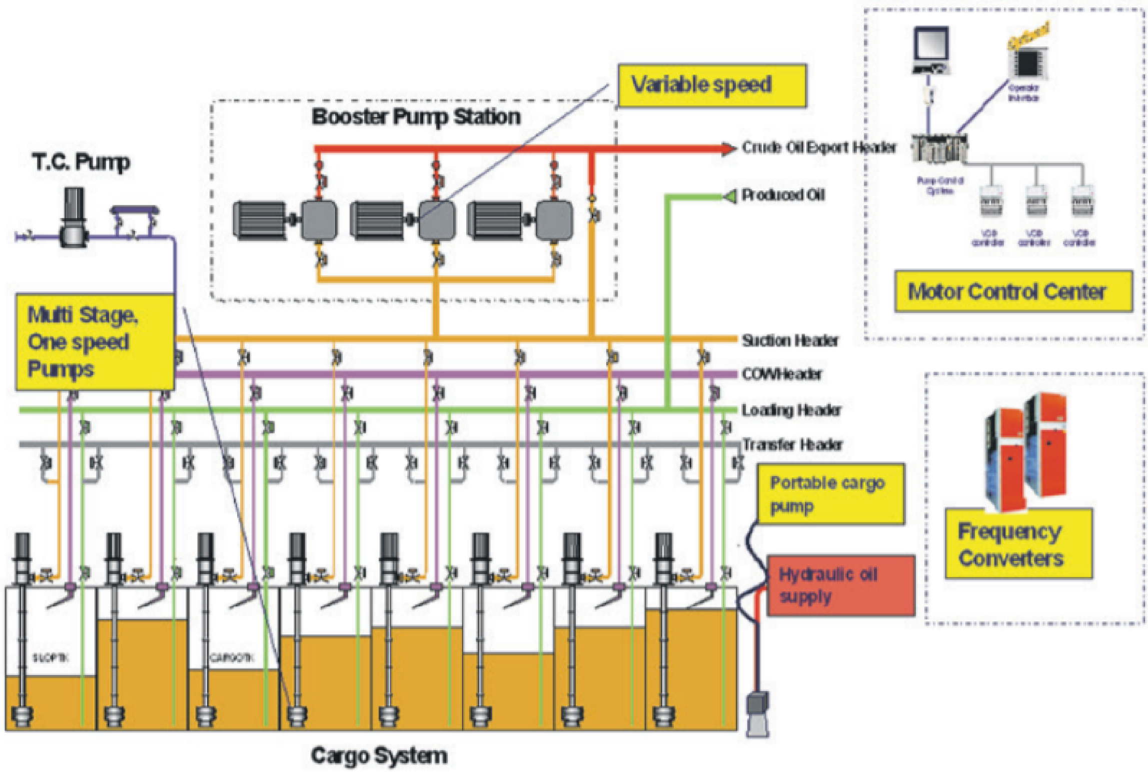
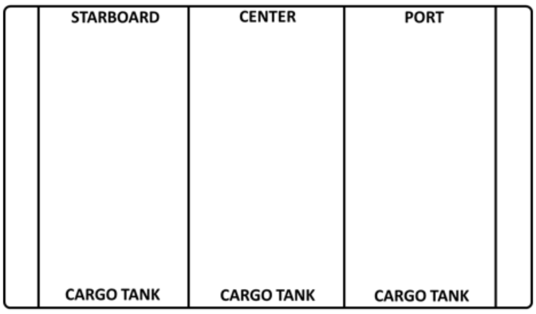


Figure 4.12: Typical FPSO Offloading System (Eureka, 2016).

Tanks

The cargo tanks are presented in the general arrangement in Figure 4.6, and it includes 20 cargo tanks. It is assumed that all cargo tanks have the same fabrication characteristics as the midship section, and that the transverse bulkheads have same plate and stiffeners thickness as longitudinal ones. The tanks are divided into 3 categories: Port Cargo Tanks, Starboard Cargo Tanks and Center Cargo Tanks. Adapting the midship configuration drawing available on Paik & Thayamballi (2007), the characteristics of the cargo tanks are as presented in Figure 4.13.



Cargo Tanks	Plate t_min (mm)	Stiffener t_min (mm)
1 (Transverse Bulkhead)	17.50	12.00
2 (Deck Shell)	30.00	15.00
3 (Longitudinal/Side Shell Cargo)	17.50	12.00
4 (Bottom Shell)	31.00	15.00
5 (Transverse Bulkhead)	17.50	12.00
6 (Longitudinal/Side Shell Cargo)	17.50	12.00

Figure 4.13: Cargo Tanks Thickness.

Offloading Hose

The offloading hose is responsible for transferring the oil from the FPSO into the shuttle taker. When designing it, one must consider not only the motion between both vessels, but also the environmental loads to which it is subjected to, such as the waves, winds and currents (Yin et al., 2017). Dynamic and static analysis are out of the scope of this master thesis, then the selection is based on information available from suppliers.

The selected equipment is Yokahoma's Sea Flex, an offshore loading and discharge hose (Yokahoma, 2018), which is designed with ISO9001 quality system. The manufacturer allows selection among four parameters: construction, flexibility, rated pressure and hose type. For this assessment, the selected hose is double carcass, with OCIMF standard and a pressure of 19 bars, hence hose type DC H-TYPE. An illustration of a double carcass house can be seen in Figure 4.14

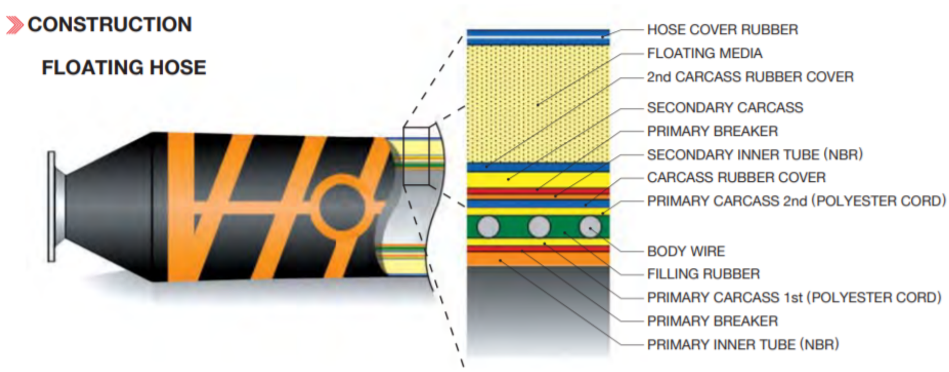


Figure 4.14: Double Carcass Floating Hose Yokahoma (2018).

Pumps

For this fictional asset, the offloading system capability is chosen to be equal to P-43/P-48, as both units have the same storage capacity. da Costa Filho (2005) states that each vessel can export 150,000 m^3 in 24 hours. This is done by 3 electrical motor driven centrifugal pumps that deliver 3,412 m^3/h each.

Not the exact same configuration will be chosen, as it was not possible to find all the necessary information online. Eureka is selected as the supplier for this study, and the chosen model is CD 400 - an electric driven pump that can deliver from 1600 m^3/h to 2000 m^3/h (Eureka, 2016). Assuming that the pumps will deliver 1800 m^3/h, then 4 cargo pumps are needed. A typical pump configuration from the manufacturer can be seen in Figure 4.15.

The brochure also states that the system is designed for easy maintenance - the pumps operates for 20,000 hours between inspection intervals (Eureka, 2016). No information is found for the electric motor inspection intervals, so the same running hours as the pumps are assumed. For redundancy, 2 extra pumps shall be selected in case any of the main offloading pumps are under maintenance or present any issues that required them to be shutdown. Thus, there is a total of 6 offloading pumps in the unit.

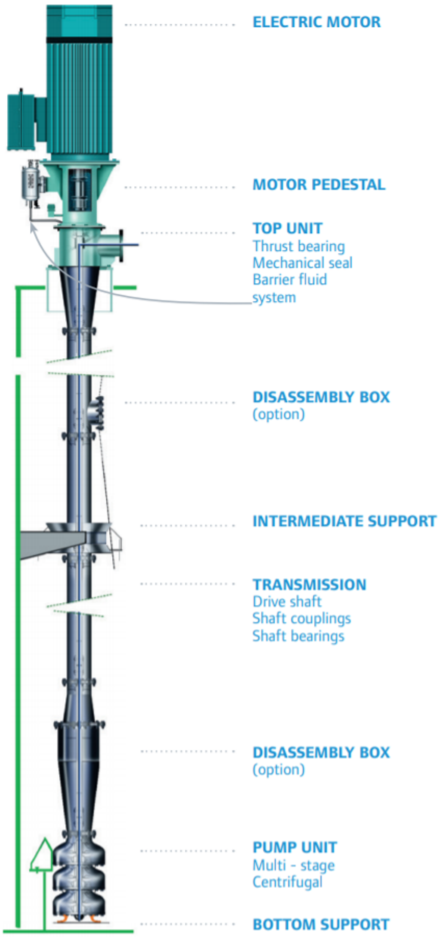


Figure 4.15: Cargo Pump Configuration (Eureka, 2016)

Distribution Systems

For the oil cargo piping, once more Schedule 40 from Pipefit (2020) are used. Only two sizes are chosen, varying from 7.11mm to 8.18mm wall thickness, the information is presented in Table 4.8.

Cargo Piping				
Location	Piping Group ID	d (mm)	t (mm)	c (mm)
Cargo Tanks	CPG 1	168.30	7.11	0.30
Cargo Tanks	CPG 2	219.10	8.18	0.30

Table 4.8: Offloading System Piping Characteristics.

4.3.4 Control and Telecommunication Systems

The control and telecommunication equipment's are defined by information available on vendors websites. Control systems are listed according to Kongsberg, while the telecommunication ones were found from ABB. However, the listed systems for this fictional FPSO are simply an illustration of what systems could be onboard the vessel, and not a real representation of the FPSO electronic systems.

Control System

The first set of control systems defined are intended for engines, engine room and automation, that can be divided into four main groups: K-Chief, K-Safe, Electrical Power Systems and Engine Monitoring System. For the automation system, one can find alarm and monitoring systems, power management, ballast control system, cargo monitoring and control, and more (Kongsberg-Maritime, 2020).

CCTV, loading system, safety deck and water tight door are examples of safety management and control systems onboard the FPSO. Electrical power systems and engine monitoring systems also require control systems. Lastly, the components within the bridge are listed, including AIS and ARPA Radar. Table 4.9 presents a full overview of the systems that could be onboard the FPSO.

Engines, Engine Room and Automation	
1	Automation System, K-Chief
1.1	Alarm and Monitoring System
1.2	Auxiliary Control System
1.3	Power Management System
1.4	Propulsion Control
1.5	Ballast System
1.6	Cargo Monitoring and Control
1.7	HVAC
2	Safety Management and Control System - K-Safe SMCS
2.1	CCTV
2.2	Safety Desk
2.3	Plan Viewer
2.4	Watertight Door
2.5	Shell Door
2.6	Low Location Light
2.7	VDR
2.8	Loading System
2.9	Information Management System (IMS)
	Electrical Power Systems
3.1	Energy Management System
3.2	Power Management System
3.3	Sensors and Machinery Monitoring
	Engine Monitoring System
4.1	Temperature Sensors, Signal Converters and Zener Barriers
4.2	Marine Pressure Transmitters
4.3	Marine Level Switches
4.4	Bearing Wear Montoring System
4.5	Water Ingress Detection System
4.6	Tank Overflow/Overfill Protection System
	Brigde

Table 4.9 continued from previous page

5	Navigation System
5.1	Gyro Compass System
5.2	Position System
5.3	Motion and Heading Sensors
5.4	ARPA Radar
5.5	AIS
5.6	Autopilot
5.7	Bridge Navigation Watch and Alert System
5.8	Conning Display
5.9	ECDIS (Electronic Chart Display)
5.10	Navigation Sensor Integrator
5.11	Stand Alone Voyage Data Recorder

Table 4.9: Control Systems for the Fictional FPSO (Kongsberg-Maritime, 2020).

Telecommunication Equipment

The telecommunication equipment onboard the FPSO are defined based on a brochure provided by ABB (ABB, 2011). The supplier divides them into 3 relevant categories: external communications, internal communication and safety and security. For this FPSO, it is selected to use the list of external and internal communication as example, as presented on Table 4.10.

	Telecommunication System
6	External Communication
6.1	Transmission/Backbone
6.2	Fibre Optic Communication
6.3	Microwave Radio
6.4	Marine Radio and GMDSS
6.5	VSAT and INMARSAT
6.6	SCADA Communication
6.7	Offloading Telemetry
6.8	Vessel Berthing System
7	Internal Communication
7.1	PABS and Telephone System
7.2	UHF Tetra Tadio
7.3	LAN/WAN and Structured Cabling System
7.4	Wireless Distribution
7.5	Paging System
7.6	Drilleræ’s Talkback
7.7	Crane Radio
7.8	Entertainment
7.9	Video Conferencing

Table 4.10: Telecommunication Systems onboard the Fictional FPSO (ABB, 2011).

Chapter 5

Case Study - Life Extension Assessment of the FPSO

This chapter presents the results by testing out the proposed methodology for decision making support in life extension of FPSO units. It starts by describing the life extension project, while giving general information on hypothesis and assumptions made over the asset's operational life. Then, a general asset condition is presented, followed by testing each marine system as identified and described before. Risk analysis are performed, all the information are gathered into scope of work and work packs are established and a cost estimation is carried out. Lastly, an economical feasibility analysis is conducted by identifying what is the minimum required oil price for the life extension project to be approved.

5.1 Assumptions and Hypothesis

In order to proceed with the life extension assessment, different hypothesis and assumptions needed to be made to align the information with a real case scenario. The following sections present the overall assumptions, however, the specific sections for each systems and analysis also present hypothesis that were not covered here.

5.1.1 The Life Extension Project

This FPSO has been operating for 15 years at the field defined in the section before. As it is located in the Brazilian Continental Shelf - a region that can be considered of hot weather - the effects of corrosion are highly seen. It has a design life of 20 years, and the assessment shall consider a life extension of 10 years - thus, operating 5 years over its initial design life. To attain compliance, no new requirements are observed, hence the same design requirement as when the FPSO was first build are expected.

5.1.2 Coating Life and Corrosion Rates

All the elements subjected to corrosion in a FPSO have some sort of protection device, such as coatings and anodes. Modelling completely the protection effects in the corrosion model was not performed here. The corrosion rates used also do not truly represent the actual corrosion rates found at oil fields in Brazil - as they are affected by temperature, fluid composition, flow velocity, humidity and many other factors. The values presented here were selected on available bibliography but not specifically refer to to the region the FPSO is located, therefore should only be used as reference.

Most of the corrosion rates are given in a $mm/year$ rate, but its effects are not constant within the entire asset life. Coating has also a defined life and only after a certain amount of time, the material starts to be corroded. All steel materials considered in this thesis are defined as carbon steel and all have a similar coating life, despite if it is a pipe or a structural element. To facilitate the assessment to be performed by the quantitative models, the coating life is characterized according to what is presented by DNVGL (2015) in guidelines. The assessment is illustrate in Figure 5.1, where it is assumed that the corrosion rate varies at the same pace as the coating life, hence no corrosion is seen before 5 years of operation, increasing uniformly until reaching the constant rate at 15 years.

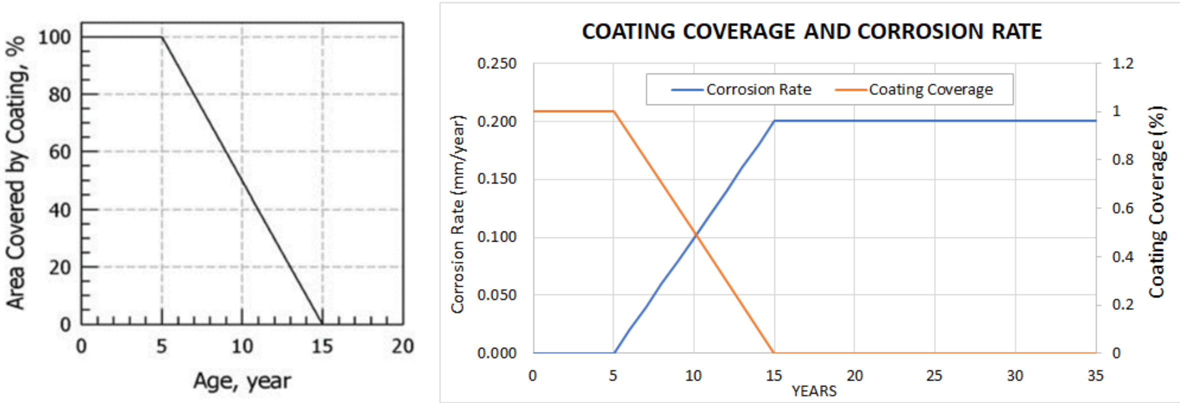


Figure 5.1: Coating Effects on Corrosion Rate based on DNVGL (2015).

The corrosion allowances used are also based on guidelines as defined in Section 3.4.1, such as DNV Rules for Ships.Pt3.Ch1.Sec2 to select the required values for steel plates and for the piping system. For pipes, the replacement criteria is the corrosion allowance - if it has been completely corroded the pipe is substituted at the equivalent year. This was necessary in order to linearize the model, but in reality the pipe may not be substituted if the corrosion allowance has been completely consumed. It depends upon the system location, complexity and other safety effects.

CIMM - Metal-Mechanic Information Center (Centro de Informação Metal-Mecânica) is used as reference to define the corrosion rate of carbon steel in seawater. The firefighting piping are assumed to be supplied with only seawater for this assessment, although other fluids could be used.

5.1.3 Production Profile and Offloading Frequency

The FPSO was responsible for 25 % of the field production during the period 2005-2020 and this rate shall be kept during the life extension period. Hence, assuming these values are constant for all the years, it is possible to calculate how many times the FPSO offloaded and to predict a value for offloads during the extension of contract. As seen in the past sections, the offloading process takes 24 hours (4 pumps are required running during 24 hours).

The results of hours in offloading process for the operating time and life extension period are seen in Table 5.1. Other set of information needed is the usage of each cargo pump into the process, which are also presented in Table 5.1. Same usage pattern is assumed for the life extension period.

Offloading Pumps		
Offloading Time	24	hours
Total Number of Offloads	863.12	
Total Offloading Hours (15 years)	20714.77	hours
Total Offloading Hours LE Period	12524.17	hours
Usage of Each Pump for Offloading		
CP 1 (Main)	88	%
CP 2 (Main)	86	%
CP 3 (Main)	93	%
CP 4 (Main)	90	%
CP 5 (Redundancy)	21	%
CP 6 (Redundancy)	18	%

Table 5.1: Offloads and Pump Usage.

5.1.4 Power Usage

For the power usage, it is considered that the FPSO has been powered by the main power generation system for 95 % of the total operating life. Hence, a 5% is selected to be the period that the engines are not working due to maintenance or other issues.

Section 4.3.1 defined the power generation system, it was seen that it is composed by 6+2 (main + redundancy) dual-fuel engines and 3 emergency power generators. Each main engine contributed differently to powering the asset, and the emergency generators only worked for 10 % of the total operating time. Table 5.2 presents the power supply profile of the power generation system.

Main Power System - Operating Profile		
Wartsila 46DF	**Usage (%)**	**Current Running Hours**
Engine 1 (Main)	80	99864.00
Engine 2 (Main)	85	106105.50
Engine 3 (Main)	81	101112.30
Engine 4 (Main)	92	114843.60
Engine 5 (Main)	88	109850.40
Engine 6 (Main)	91	113595.30
Engine 6 (Aux)	21	26214.30
Engine 6 (Aux)	26	32455.80
Wartsila 20	**Usage (%)**	**Current Running Hours**
Generator 1	20	2628.00
Generator 2	15	1971.00
Generator 3	13	1708.20

Table 5.2: Main Power System - Operating Profile.

5.1.5 Maintenance and Overhauls

This FPSO is assumed to be maintained according to best practice - that is if an overhaul, inspection or replacement was required during the operating life, it was performed. Hence, if a quantitative result shows that the life time is reached within the operating life, it was substituted for a new one and therefore the life is restarted for that period. This way one can predict how many replacements/overhauls were performed during the operating life and calculate how much of it is left for the life extension period.

5.2 Case Study - FPSO Life Extension Assessment

This section presents the results and discussions of testing out the methodology in a mock up vessel. Stage 1 in the methodology is defining the life extension requirements, which was already performed while defining the mock-up vessel in the previous sections. The FPSO condition is presented as a general overview, with information only in level 1 systems. This was done because the marine systems selected were also assessed considering the qualitative condition, but now on subsystems and components level. The analysis follows by performing the qualitative assessment, quantitative assessment, and risk analysis for each of the subsystems selected for the study. Then, all outcomes are gathered into work packs and a simple cost estimation is performed, and are used as input to the economical feasibility analysis performed.

5.2.1 General Asset Condition

The list of systems onboard the FPSO are based on SFI system list available on Shetelig (2013), however, here it is only considered level 1 systems. Applying the proposed framework for general asset condition, the results showed that the unit is in overall good, with a few systems in bad condition or requiring updates.

Maintenance results are also in accordance with the assumption that the unit is well maintained. Most of the system are up to date with maintenance, with few not being maintained or with backlog. Considering life extension, almost all of the scope can be carried out during normal operation offshore.

Nevertheless, some other systems require dry dock, yard stay or work offshore during production shutdown. Practically, some work defined as offshore campaign can be done during yard stay, and vice versa. The actual decision upon on this depends on the extend of work to be carried out at the yard and the amount of time the unit will be there. For example, the ship owner can decide on doing an overhaul earlier when steel renewal is being carried out while in yard, rather than after some time during life extension production time frame. Figure 5.2 presents the main results for the fictional FPSO after testing out the proposed framework for condition assessment, and the full analysis is available on Appendix C.1 - General Asset Condition.

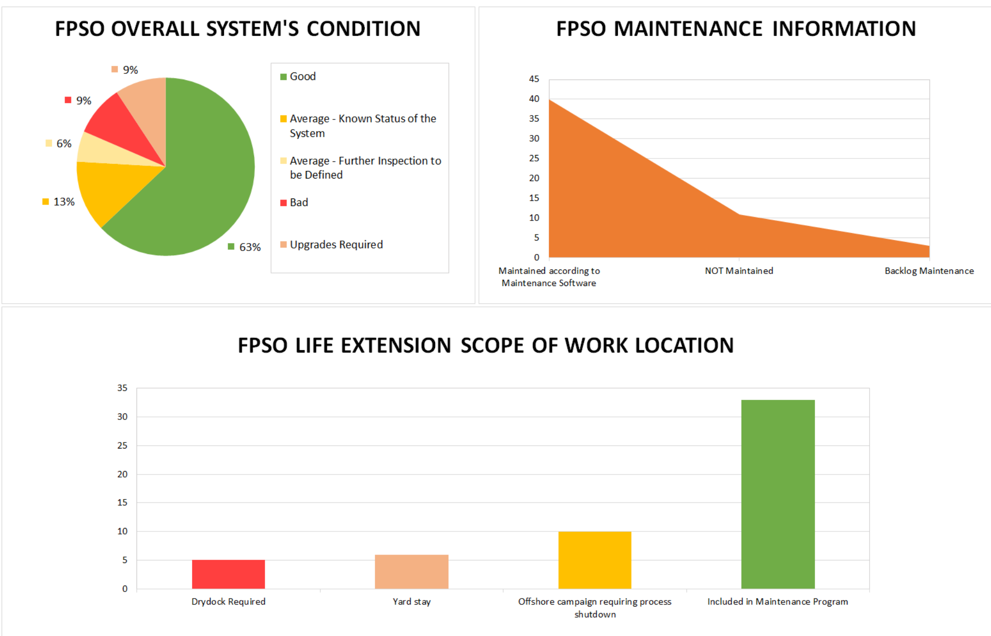


Figure 5.2: The FPSO General Condition.

5.2.2 Structural Systems

For the structural systems quantitative assessment, just the midship section is considered. The unit has no turret, as it is spread-moored and it was not possible to find the required data for the flare structure, helideck or accommodation. Hence, these subsystems have only qualitative assessments. The next subsections present the main results of the analysis, and the full results are available on Appendix C.2 - Structural Assessment.

Structural Condition

The "As Is" condition status of the structural systems starts by defining a list of generic elements. These include the bottom and main deck, side shells, the accommodation blocks, helideck and flare. It is carried out evaluating the current condition, and then predicting a possible scope of work. The full qualitative assessment is available on Figure 5.3.

ID	ELEMENT	INFORMATION SOURCE	USAGE	USAGE STATUS	MAINTENANCE	CONDITION	OBSOLETE	EXPECTED SCOPE	TYPE OF WORK	CRITICAL SPARE PARTS	SCOPE LOCATION
1	Overall Bottom Deck Midship	Maintenance Software	InService	Working According to Specifications	Not Maintained	Average - Further Inspection to be Defined	NO	Reinforcement of steel plates and stiffeners, as well as recoating	Life Extension	NO	Yard Stay
2	PBT	Maintenance Software	InService	Working According to Specifications	Not Maintained	Average - Further Inspection to be Defined	NO	Reinforcement of steel plates and stiffeners, as well as recoating	Life Extension	NO	Yard Stay
2	SBT	Maintenance Software	InService	Working According to Specifications	Not Maintained	Average - Further Inspection to be Defined	NO	Reinforcement of steel plates and stiffeners, as well as recoating	Life Extension	NO	Yard Stay
2	PCT	Maintenance Software	InService	Working According to Specifications	Not Maintained	Average - Further Inspection to be Defined	NO	Reinforcement of steel plates and stiffeners, as well as recoating	Life Extension	NO	Yard Stay
2	SCT	Maintenance Software	InService	Working According to Specifications	Not Maintained	Average - Further Inspection to be Defined	NO	Reinforcement of steel plates and stiffeners, as well as recoating	Life Extension	NO	Yard Stay
2	CCT	Maintenance Software	InService	Working According to Specifications	Not Maintained	Average - Further Inspection to be Defined	NO	Reinforcement of steel plates and stiffeners, as well as recoating	Life Extension	NO	Yard Stay
1	Port Side Shell - Outside Hull	Maintenance Software	InService	Working According to Specifications	Not Maintained	Average - Further Inspection to be Defined	NO	Reinforcement of steel plates and stiffeners, as well as recoating	Life Extension	NO	Drydock Required
2	PBT	Maintenance Software	InService	Working According to Specifications	Not Maintained	Average - Further Inspection to be Defined	NO	Reinforcement of steel plates and stiffeners, as well as recoating	Life Extension	NO	Drydock Required
1	Starboard Side Shell - Outside Hull	Maintenance Software	InService	Working According to Specifications	Not Maintained	Average - Further Inspection to be Defined	NO	Reinforcement of steel plates and stiffeners, as well as recoating	Life Extension	NO	Drydock Required
2	SBT	Maintenance Software	InService	Working According to Specifications	Not Maintained	Average - Further Inspection to be Defined	NO	Reinforcement of steel plates and stiffeners, as well as recoating	Life Extension	NO	Drydock Required
1	Main Process Deck Shell	Maintenance Software	InService	Working According to Specifications	Maintained	Good	NO	Regular Maintenance	Life Extension	NO	Yard Stay
2	PBT	Maintenance Software	InService	Working According to Specifications	Maintained	Good	NO	Regular Maintenance	Life Extension	NO	Yard Stay
2	SBT	Maintenance Software	InService	Working According to Specifications	Maintained	Good	NO	Regular Maintenance	Life Extension	NO	Yard Stay
2	PCT	Maintenance Software	InService	Working According to Specifications	Maintained	Good	NO	Regular Maintenance	Life Extension	NO	Yard Stay
2	SCT	Maintenance Software	InService	Working According to Specifications	Maintained	Good	NO	Regular Maintenance	Life Extension	NO	Yard Stay
2	CCT	Maintenance Software	InService	Working According to Specifications	Maintained	Good	NO	Regular Maintenance	Life Extension	NO	Yard Stay
1	Accommodati on Block	Maintenance Software	InService	Working According to Specifications	Maintained	Good	NO	Regular Maintenance	Life Extension	NO	Normal Maintenace
2	Windows	Maintenance Software	InService	Working According to Specifications	Maintained	Good	NO	Regular Maintenance	Life Extension	NO	Normal Maintenace
2	Inside Decks	Maintenance Software	InService	Working According to Specifications	Maintained	Good	NO	Regular Maintenance	Life Extension	NO	Normal Maintenace
2	External Accomodation Walls	Maintenance Software	InService	Working According to Specifications	Not Maintained	Bad	NO	Regular Maintenance	Life Extension	NO	Normal Maintenace
2	Internal Accomodation Walls	Maintenance Software	InService	Working According to Specifications	Maintained	Good	NO	Regular Maintenance	Life Extension	NO	Normal Maintenace
2	Process Deck Level Plate	Maintenance Software	InService	Working According to Specifications	Not Maintained	Average - Further Inspection to be Defined	NO	Reinforcement of steel plates and stiffeners, as well as recoating	Life Extension	NO	Normal Maintenace
1	Helideck	Maintenance Software	InService	Working According to Specifications	Maintained	Good	NO	Regular Maintenance	Life Extension	NO	Normal Maintenace
2	Helideck Supports	Maintenance Software	InService	Working According to Specifications	Maintained	Good	NO	Regular Maintenance	Life Extension	NO	Normal Maintenace
2	Helideck Deck	Maintenance Software	InService	Working According to Specifications	Maintained	Good	NO	Regular Maintenance	Life Extension	NO	Normal Maintenace
1	Flare Structure	Maintenance Software	InService	Working According to Specifications	Maintained	Good	NO	Regular Maintenance	Life Extension	NO	Normal Maintenace
2	Flare Deck Support	Maintenance Software	InService	Working According to Specifications	Maintained	Good	NO	Regular Maintenance	Life Extension	NO	Normal Maintenace

Figure 5.3: Qualitative Assessment of Structural Components

The results for the fictional asset shows that only the accommodation external area and its connection with the process deck are not maintained. Good condition is seen in many systems, while only the external accommodation walls are classified as bad. Some areas inside the hull are defined to be in an average condition and further inspection are necessary there. This is expected as one region is the bottom area of the tanks, while the others are the external and submerged areas of the hull.

Quantitative Model - Corrosion Assessment

The quantitative model to be use for structural systems forecasts the effects of corrosion over time - from the start of operation (Year 0 - 1995) and up to 40 years of production. The minimum thickness values are identified from the midship section provided on Appendix A.1 - Structural Components - whenever it was necessary, assumptions were made regarding plate and stiffeners thickness. The corrosion allowances were defined based on DNV GL Ship Rules - Pt.3 Ch.1 Hull Structural Design. All the ballast tanks are assumed to be coated, while the cargo tanks are coated in a region within 2m above baseline and 2m below main deck.

For the ballast tanks regions, it is considered that seawater is used, which is the same fluid that the external shells are exposed to. The renewal thickness was calculate as proposed by DNVGL-CG-0172 and presented in section 3.4.1. The corrosion rate for seawater is assumed to be 0.13 mm/year (CIMM, 2020) when it reaches the constant value. Tropical Marine atmospheric corrosion value selected is 0.51 mm/year (CIMM, 2020), and for the cargo tanks, a typical value of 0.1 mm/year was chosen (OCIMF, 1997). Figure 5.4 gives an overview of the fluids and in which region are they influencing in the midship section.

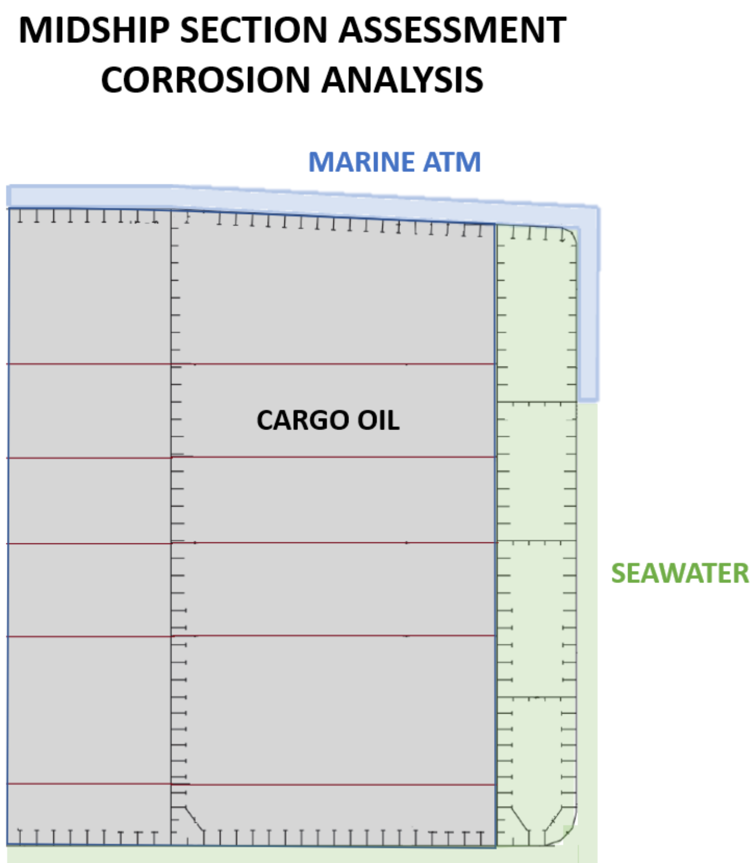


Figure 5.4: Fluids and Regions used in Structural Corrosion Assessment.

Two sets of lifespans are calculated based on the two requirements: corrosion allowance and renewal thickness. The results showed that most of the corrosion allowance is consumed before the renewal value is achieved, and as expected, thicker plates and stiffeners have longer life's than the thinner ones.

For the ballast tanks plates, the first corrosion allowance is consumed in 12 years, and a renewal in steel is needed in 14 years for the plates. Considering the stiffeners, the first allowance consumption happens in 17 years, and only in 29 years is steel renewal required.

For the cargo tanks, a value of 10 years is found for the first group of plates to have their corrosion allowance consumed, and 15 years to require steel renewal. For stiffeners, the results are 20 years for corrosion allowance and 35 for steel renewal.

The model predicts the effects starting on Year 0 of operation, hence in 1995, therefore a simple calculation is made for the total operation time and life extension period. Based on the assessment, the "As Is" condition of the forecasted corrosion of the unit can be found in Figure 5.5. Some areas have already reached the acceptable corrosion allowance and/or require steel renewal, while others are still within the acceptable limits.

It can be seen that the model resulted in worse results for plates than for stiffeners, and this is due to the type of corrosion each element is subjected too. In most cases, the stiffeners are only corroded by internal fluids of the tanks (seawater or oil), while the plates can be corroded in each side by one of the fluids and, or even the marine atmosphere. Each thickness group life period until reaching one of the criterion can be found on Appendix C.2 - Structural Assessment.

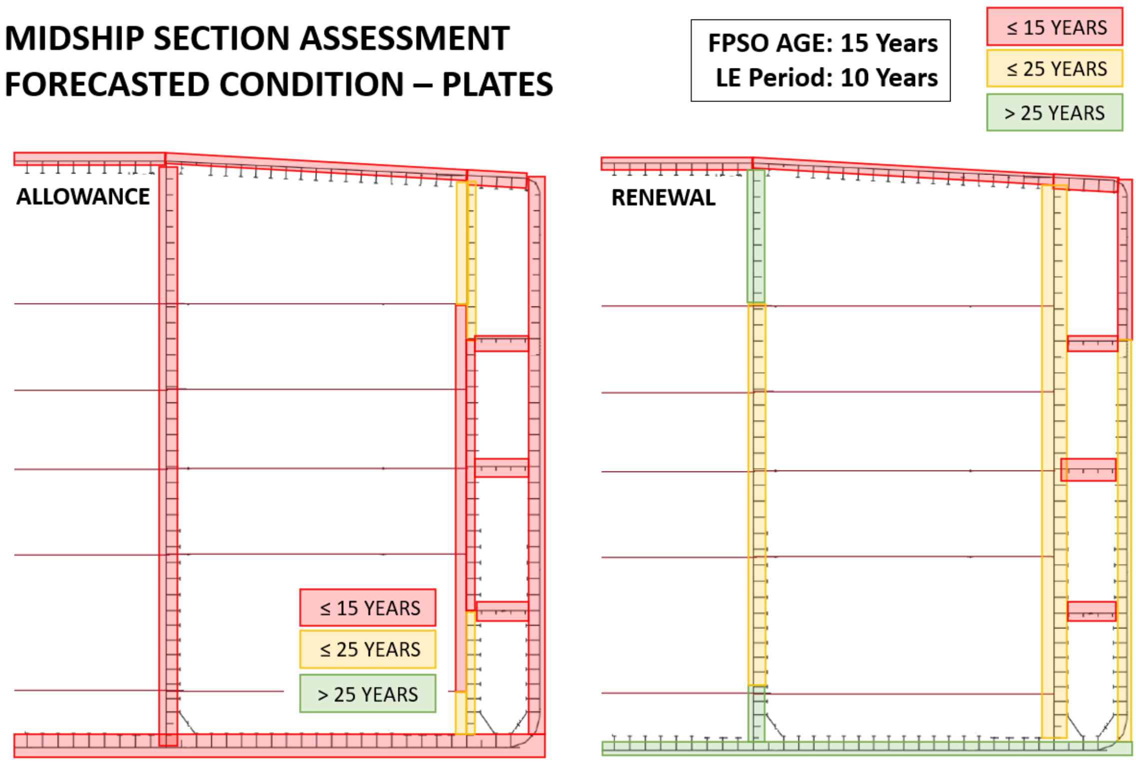


Figure 5.5: Midship Section Life Span - Plates.

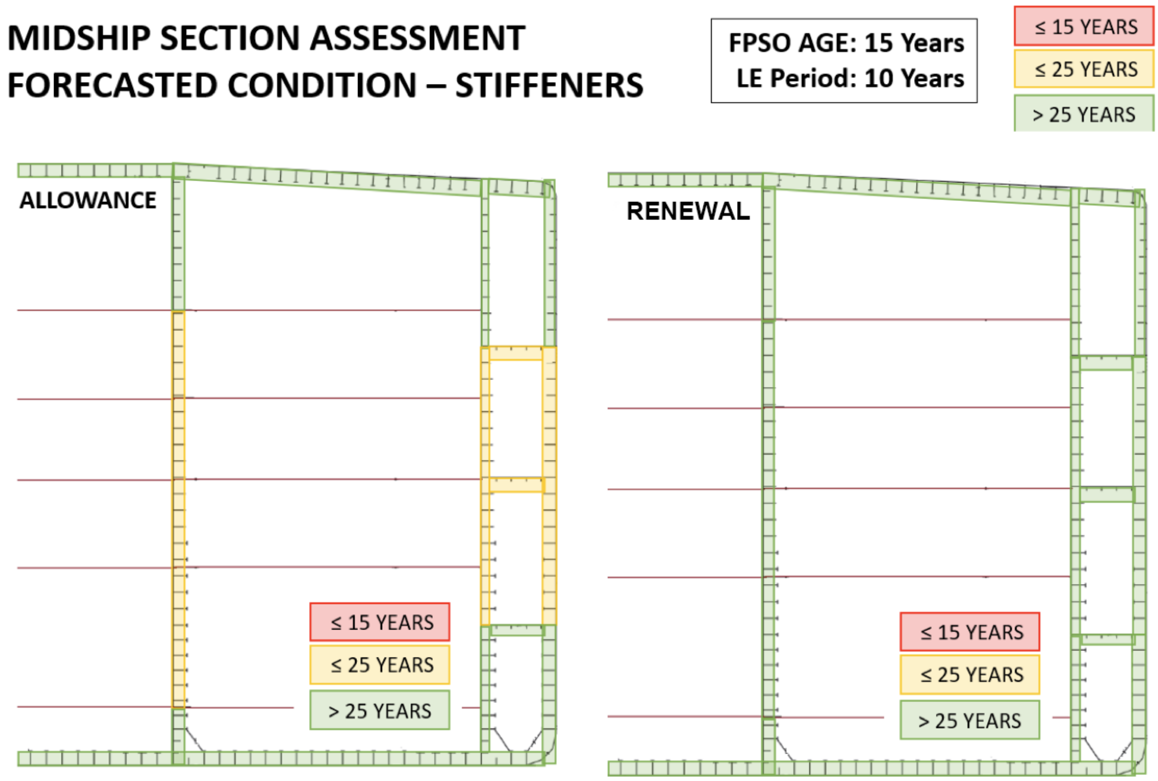


Figure 5.6: Midship Section Life Span - Stiffeners.

Risk Analysis and Risk Mitigation

The risk analysis starts by gathering all the information from quantitative and qualitative assessment made before into a spreadsheet. The results are presented on Table 5.3. Using the outcomes of "As Is" condition and corrosion forecast, the FMEA identified 3 main regions that require mitigation actions.

The first region considers the external accommodation walls that had two different risks identified - 1.3.a and 1.3.b. Both have the same failure cause: excessive corrosion/damage in accommodation, but different failure modes. The first failure mode considers the most extreme scenario, where the entire accommodation could collapse, leading to a local effect of not having a place for the crew to be accommodated in - what would lead to a stop of production. The likelihood was decided into possible and its severity would be catastrophic, hence a risk of 15 was found.

The second risk considers that the possible failure mode would be the collapse of some areas of the accommodation block. This could cause the loss of rooms for some crew members and would require that other people were assigned to fix it - what could cause delay in maintenance from other areas of the asset. This event is assumed to be possible, and the consequence would be moderate, as some other important systems could have its maintenance postponed - a risk of 9 was found, therefore within the ALARP area.

The second risk associated with the accommodation are related to the connection with the process deck level. From the qualitative assessment, it was observed that the plates are in regular condition and require some work to be renewed. Similar failure modes, effects and consequences as for the external walls were identified, where one of the risks sits in the ALARP zone and the other in intolerable area. Table 5.7 presents a general overview of the outcomes from the accommodation region.

REF	System/Subsystem/Element	Life Extension Assessment Outcome
1	Accomodation Block	
1.1.a	Windows	Good condition, will need some replacement during LE period
1.1.b	Windows	Good condition, will need some replacement during LE period
1.2	Inside Decks	Good condition, needs a few renewal and upgrades
1.3.a	External Accomodation Walls	In bad condition, will require a full painting of the area
1.3.b	External Accomodation Walls	In bad condition, will require a full painting of the area
1.4	Internal Accomodation Walls	Good condition, needs a few renewal and upgrades
1.5.a	Process Deck Level Plate	Average condition, needs more inspection and possible upgrades during LE period
1.5.b	Process Deck Level Plate	Average condition, needs more inspection and possible upgrades during LE period
2	Flare	
2.1	Flare Deck Support	Good condition, needs a few renewal and upgrades
3	Helideck	
3.1	Helideck Supports	Good condition, needs a few renewal and upgrades
3.2	Helideck Deck	Good condition, needs a few renewal and upgrades
4	Midship Section	
4.1	Port Side Shell	
4.1.a	Ballast Tanks Plates	Most of corrosion allowance has already been consumed. Side shell exposed to marine atmosphere already needs steel renewal, while the remaining will require within the LE Period (<25 years).
4.1.b	Ballast Tanks Stiffeners	Ballast tanks 2 and 3 stiffeners will have corrosion allowance consumed during LE Period, but no stiffeners will be below the steel renewal requirement during same period.
4.2	Starboard Side Shell	
4.2.a	Ballast Tanks Plates	Most of corrosion allowance has already been consumed. Side shell exposed to marine atmosphere already needs steel renewal, while the remaining will require within the LE Period (<25 years).
4.2.b	Ballast Tanks Stiffeners	Ballast tanks 2 and 3 stiffeners will have corrosion allowance consumed during LE Period, but no stiffeners will be below the steel renewal requirement during same period.
4.3	Bottom Shell	
4.3.a	Port Ballast Tank Plate	The forecasted model shows that the corrosion allowance has already been consumed but the renewal value is not reach withing LE Period.
4.3.b	Port Ballast Tank Stiffener	No issues to be found on the stiffeners - nor corrosion allowance, nor renewal thickness are reach during LE Period.
4.3.c	Starboard Ballast Tank Plate	The forecasted model shows that the corrosion allowance has already been consumed but the renewal value is not reached withing LE Period.
4.3.d	Starboard Ballast Tank Stiffener	No issues to be found on the stiffeners - nor corrosion allowance, nor renewal thickness are reach during LE Period.
4.3.e	Port Cargo Tank Plate	The forecasted model shows that the corrosion allowance has already been consumed but the renewal value is not reached withing LE Period.
4.3.f	Port Cargo Tank Stiffener	No issues to be found on the stiffeners - nor corrosion allowance, nor renewal thickness are reach during LE Period.
4.3.g	Starboard Cargo Tank Plate	The forecasted model shows that the corrosion allowance has already been consumed but the renewal value is not reached withing LE Period.
4.3.h	Starboard Cargo Tank Stiffener	No issues to be found on the stiffeners - nor corrosion allowance, nor renewal thickness are reach during LE Period.
4.3.i	Center Cargo Tank Plate	The forecasted model shows that the corrosion allowance has already been consumed but the renewal value is not reached withing LE Period.
4.3.j	Center Cargo Tank Stiffener	No issues to be found on the stiffeners - nor corrosion allowance, nor renewal thickness are reach during LE Period.
4.4	Cargo Tanks Longitudinal Bulkhead	
4.4.a	Port Cargo Tank Plate	Corrosion allowance is already consumed, but only the regions not coated (2m above baseline and 2m below main deck) will need steel renewal work during LE Period.
4.4.b	Port Cargo Tank Stiffener	Only the stiffeners located in the non-coated region (2m below main deck and 2m above baseline) will have corrosion allowance consumed within LE Period, but not will require steel renewal.
4.4.c	Starboard Cargo Tank Plate	Corrosion allowance is already consumed, but only the regions not coated (2m above baseline and 2m below main deck) will need steel renewal work during LE Period.
4.4.d	Starboard Cargo Tank Stiffener	Only the stiffeners located in the non-coated region (2m below main deck and 2m above baseline) will have corrosion allowance consumed within LE Period, but not will require steel renewal.

Table 5.3: Structural Systems Life Extension Assessment.

REF	Element	LE Assessment Outcome	Failure Cause or Mechanism	Failure Mode	Local Effects	Global Effect	Consequences	L	S	R
1	Accomodation Block									
1.3.a	External Accomodation Walls	In bad condition, will require a full painting of the area	Excessive corrosion/damage in accommodation	Colapse of accomodation block	No place to accommodate crew	Suspention of production until problem	Loss of production days	3	5	15
1.3.b	External Accomodation Walls	In bad condition, will require a full painting of the area	Excessive corrosion/damage in accommodation	Colapse of some sections of accommodatio	Some rooms break down	People have to be assigned to fix it	People have to be accommodate somewhere else	3	3	9
1.5.a	Process Deck Level Plate	Average condition, needs more inspection and possible upgrades duuring LE period	Excessive corrosion/damage in connection level between accommodation block and	Colapse of accomodation block	Accommodation block is no longer safe - no place to accommodate crew	Suspention of production until problem is fixed	Loss of production days	2	5	10
1.5.b	Process Deck Level Plate	Average condition, needs more inspection and possible upgrades duuring LE period	Excessive corrosion/damage in connection level between accommodation block and	Cracking and breaking of some of the supporting	Supporting region corrored	People have to be assigned to fix it	Some other maintenance task may have do be rescheduled	2	3	6

Figure 5.7: Structural System Risk Analysis - Accommodation Outcomes.

The midhship section is the second group that presented risks to be mitigated, divided mainly into the process deck, side shells, longitudinal cargo tank bulkhead and bottom hull. If any of those are to fail the consequences are catastrophic, as in any of theses regions crackings would cause an opening in the hull, thus water can enter the unit leading to capszing or sinking and therefore huge impacts into environment, people, reputation, asset, and operation.

From the forecasted results, it was seen that some plates already have their corrosion allowance totally consumed, while others would be consumed during the life extension period. However, the steel renewal should be kept as the main criteria for this assessment. Hence, the critical areas are the process deck level, the side shell of the hull not immersed in the ocean, and the longitudinal bulkheads separating the cargo tanks.

As stated previously, the worst case scenario is used as the consequence, while the life span guides the likelihood of each failure mode. The plates that already need (based on "As Is" condition and forecasted corrosion) renewal have higher likelihoods of failing than the ones that will reach the renewal criteria during the life extension period.

In order to reduce the risk analysis outcomes, the assessment is made in a higher level. Therefore, it is not considered individually each result, but as whole for the defined sections. The results are presented in Figure 5.8.

The mitigation actions are proposed based on the risk ranking results - all the values within the intolerable area shall be mitigated. Although the elements are located in different regions, the mitigation action is pretty much the same: perform the necessary work so that the likelihood of a catastrophic event happening can be reduced. The risks within ALARP region have no proposed mitigation as the likelihood is the lowest. Figure 5.9 presents the results and reduction between initial and mitigated risks.

REF	System/Subsystem/Element	Life Extension Assessment Outcome	Failure Cause or Mechanism	Failure Mode	Detection of Failure	Local Effects	Global Effect	Consequences	L	S	R
4	Midship Section										
4.1	Port Side Shell										
4.1.a	Ballast Tanks Plates	Most of corrosion allowance has already been consumed. Side shell exposed to marine atmosphere already needs steel renewal, while the remaining will require within the LE Period (<25 years).	Corrosion damage	Cracking due to corrosion effects	Regular Inspection	Minor damage in one region	Complete Structural Colapse	Asset sinking or capsizing	4	5	20
4.1.b	Ballast Tanks Stiffeners	Ballast tanks 2 and 3 stiffeners will have corrosion allowance consumed during LE Period, but no stiffeners will be below the steel renewal requirement during same period.	Corrosion damage	Cracking due to corrosion effects	Regular Inspection	Minor damage in one region	Complete Structural Colapse	Asset sinking or capsizing	1	5	5
4.2	Starboard Side Shell										
4.2.a	Ballast Tanks Plates	Most of corrosion allowance has already been consumed. Side shell exposed to marine atmosphere already needs steel renewal, while the remaining will require within the LE Period (<25 years).	Corrosion damage	Cracking due to corrosion effects	Regular Inspection	Minor damage in one region	Complete Structural Colapse	Asset sinking or capsizing	4	5	20
4.2.b	Ballast Tanks Stiffeners	Ballast tanks 2 and 3 stiffeners will have corrosion allowance consumed during LE Period, but no stiffeners will be below the steel renewal requirement during same period.	Corrosion damage	Cracking due to corrosion effects	Regular Inspection	Minor damage in one region	Complete Structural Colapse	Asset sinking or capsizing	1	5	5
4.3	Bottom										
4.3.a	Port Ballast Tank Plate	The forecasted model shows that the corrosion allowance has already been consumed but the renewal value is not reached withing LE Period.	Corrosion damage	Cracking due to corrosion effects	Regular Inspection	Minor damage in one region	Complete Structural Colapse	Asset sinking or capsizing	1	5	5
4.3.b	Port Ballast Tank Stiffener	No issues to be found on the stiffeners - nor corrosion allowan, nor renewal thickness are reachead during LE Period.	Corrosion damage	Cracking due to corrosion effects	Regular Inspection	Minor damage in one region	Complete Structural Colapse	Asset sinking or capsizing	1	5	5
4.3.c	Starboard Ballast Tank Plate	The forecasted model shows that the corrosion allowance has already been consumed but the renewal value is not reached withing LE Period.	Corrosion damage	Cracking due to corrosion effects	Regular Inspection	Minor damage in one region	Complete Structural Colapse	Asset sinking or capsizing	1	5	5
4.3.d	Starboard Ballast Tank Stiffener	No issues to be found on the stiffeners - nor corrosion allowan, nor renewal thickness are reachead during LE Period.	Corrosion damage	Cracking due to corrosion effects	Regular Inspection	Minor damage in one region	Complete Structural Colapse	Asset sinking or capsizing	1	5	5
4.3.e	Port Cargo Tank Plate	The forecasted model shows that the corrosion allowance has already been consumed but the renewal value is not reached withing LE Period.	Corrosion damage	Cracking due to corrosion effects	Regular Inspection	Minor damage in one region	Complete Structural Colapse	Asset sinking or capsizing	1	5	5
4.3.f	Port Cargo Tank Stiffener	No issues to be found on the stiffeners - nor corrosion allowan, nor renewal thickness are reachead during LE Period.	Corrosion damage	Cracking due to corrosion effects	Regular Inspection	Minor damage in one region	Complete Structural Colapse	Asset sinking or capsizing	1	5	5
4.3.g	Starboard Cargo Tank Plate	The forecasted model shows that the corrosion allowance has already been consumed but the renewal value is not reached withing LE Period.	Corrosion damage	Cracking due to corrosion effects	Regular Inspection	Minor damage in one region	Complete Structural Colapse	Asset sinking or capsizing	1	5	5
4.3.h	Starboard Cargo Tank Stiffener	No issues to be found on the stiffeners - nor corrosion allowan, nor renewal thickness are reachead during LE Period.	Corrosion damage	Cracking due to corrosion effects	Regular Inspection	Minor damage in one region	Complete Structural Colapse	Asset sinking or capsizing	1	5	5
4.3.i	Center Cargo Tank Plate	The forecasted model shows that the corrosion allowance has already been consumed but the renewal value is not reached withing LE Period.	Corrosion damage	Cracking due to corrosion effects	Regular Inspection	Minor damage in one region	Complete Structural Colapse	Asset sinking or capsizing	1	5	5
4.3.j	Center Cargo Tank Stiffener	No issues to be found on the stiffeners - nor corrosion allowan, nor renewal thickness are reachead during LE Period.	Corrosion damage	Cracking due to corrosion effects	Regular Inspection	Minor damage in one region	Complete Structural Colapse	Asset sinking or capsizing	1	5	5
4.4	Cargo Tanks Longitudinal Bulkhead										0
4.4.a	Port Cargo Tank Plate	Corrosion allowance is already consumed, but only the regions not coated (2m above baseline and 2m below main deck) will need steel renewal work during LE Period.	Corrosion damage	Cracking due to corrosion effects	Regular Inspection	Minor damage in one region	Complete Structural Colapse	Asset sinking or capsizing	2	4	8
4.4.b	Port Cargo Tank Stiffener	Only the stiffeners located in the non-coated region (2m below main deck and 2m above baseline) will have corrosion allowance consumed within LE Period, but not will require steel renewal.	Corrosion damage	Cracking due to corrosion effects	Regular Inspection	Minor damage in one region	Complete Structural Colapse	Asset sinking or capsizing	2	4	8
4.4.c	Starboard Cargo Tank Plate	Corrosion allowance is already consumed, but only the regions not coated (2m above baseline and 2m below main deck) will need steel renewal work during LE Period.	Corrosion damage	Cracking due to corrosion effects	Regular Inspection	Minor damage in one region	Complete Structural Colapse	Asset sinking or capsizing	2	4	8
4.4.d	Starboard Cargo Tank Stiffener	Only the stiffeners located in the non-coated region (2m below main deck and 2m above baseline) will have corrosion allowance consumed within LE Period, but not will require steel renewal.	Corrosion damage	Cracking due to corrosion effects	Regular Inspection	Minor damage in one region	Complete Structural Colapse	Asset sinking or capsizing	2	4	8
4.5	Process Deck Level Plate	The corrosion allowance has already been consumed and the plates need steel renewal as of today.	Corrosion damage	Cracking due to corrosion effects	Regular Inspection	Minor damage in one region	Complete Structural Colapse	Asset sinking or capsizing	3	5	15

Figure 5.8: Structural System Risk Analysis - Midship Section Outcomes.

REF	System/Subsystem /Element	Life Extension Assessment Outcome	L	S	R	Mitigation Action	LM	SM	MR	RR
1.3.a	External Accomodation Walls	In bad condition, will require a full painting of the area	3	5	15	Perform the necessary refurbishments and apply coating in the external walls	1	5	5	0.67
1.3.b	External Accomodation Walls	In bad condition, will require a full painting of the area	3	3	9	Perform the necessary refurbishments and apply coating in the external walls	1	5	5	0.44
1.5.a	Process Deck Level Plate	Average condition, needs more inspection and possible upgrades during LE period	2	5	10	Perform the necessary refurbishments and reinforcements	1	5	5	0.50
1.5.b	Process Deck Level Plate	Average condition, needs more inspection and possible upgrades during LE period	2	3	6	Perform the necessary refurbishments and reinforcements	1	3	3	0.50
4	Midship Section									
4.1	Port Side Shell									
4.1.a	Ballast Tanks Plates	Most of corrosion allowance has already been consumed. Side shell exposed to marine atmosphere already needs steel renewal, while the remaining will require within the LE Period (<25 years).	4	5	20	Reinforce or replace as necessary. For the plates that reach criteria corrosion allowance during LE period, recoate them.	1	5	5	0.75
4.2	Starboard Side Shell									
4.2.a	Ballast Tanks Plates	Most of corrosion allowance has already been consumed. Side shell exposed to marine atmosphere already needs steel renewal, while the remaining will require within the LE Period (<25 years).	4	5	20	Reinforce or replace as necessary. For the plates that reach criteria corrosion allowance during LE period, recoate them.	1	5	5	0.75
4.5	Process Deck Level Plate	The corrosion allowance has already been consumed and the plates need steel renewal as of today.	3	5	15	Reinforce or replace as necessary. For the plates that reach criteria corrosion allowance during LE period, recoate them.	1	5	5	0.67

Figure 5.9: Structural System Mitigation Actions.

5.2.3 Firefighting System

The firefighting system studies the overall condition, and forecasts corrosion effects of the distribution systems. The pump analysis is also qualitative, as well as sprinkles, valves and hawsers. Some assumptions were made into the amount of valves that require replacements. Also, it is expected that this system has run for as little as possible.

Firefighting System Condition

The current condition of the unit is in overall good, apart from some valves that are needing replacement and a pump that needs further inspection. All the system are in use and working according to specifications, and the maintenance program is updated.

It is assumed that a total of 10 valves need replacement in all the firefighting system and that this work can be done during normal maintenance offshore. As the firefighting system is not used frequently, an overhaul could be done in order to check its actual condition. The pipes are brand new - as is seen in the quantitative model next - and no major issues are found on them. Figure 5.10 presents the qualitative information on the firefighting system condition.

Although the firefighting system has a pump, it does not fit into the analysis of running hours. It is hoped that the system does not need to be run - or at least be run as little as possible - as no fire is expected during the operation phase. For this assessment, it is assumed that the system had to be run only once during its operating life.

ID	ELEMENT	INFORMATION SOURCE	USAGE	USAGE STATUS	MAINTENANCE	CONDITION	OBSOLETE	EXPECTED SCOPE	TYPE OF WORK	CRITICAL SPARE PARTS	SCOPE LOCATION
1	Deluge and Distribution System										
1.1	Accommodation										
1.1.a	APG 1	Operation Experience	InService	Working According to Specifications	Maintained	Good	NO	Normal Maintenance	Life Extension	NO	Include in Maintenance Program
1.1.b	APG 2	Operation Experience	InService	Working According to Specifications	Maintained	Good	NO	Normal Maintenance	Life Extension	NO	Include in Maintenance Program
1.1.c	APG 3	Operation Experience	InService	Working According to Specifications	Maintained	Good	NO	Normal Maintenance	Life Extension	NO	Include in Maintenance Program
1.2	Machinery Room										
1.2.a	MRPG 1	Operation Experience	InService	Working According to Specifications	Maintained	Good	NO	Normal Maintenance	Life Extension	NO	Include in Maintenance Program
1.2.b	MRPG 2	Operation Experience	InService	Working According to Specifications	Maintained	Good	NO	Normal Maintenance	Life Extension	NO	Include in Maintenance Program
1.2.c	MRPG 3	Operation Experience	InService	Working According to Specifications	Maintained	Good	NO	Normal Maintenance	Life Extension	NO	Include in Maintenance Program
1.2.d	MRPG 4	Operation Experience	InService	Working According to Specifications	Maintained	Good	NO	Normal Maintenance	Life Extension	NO	Include in Maintenance Program
1.3	Control System										
1.3.a	CRP G1	Operation Experience	InService	Working According to Specifications	Maintained	Good	NO	Normal Maintenance	Life Extension	NO	Include in Maintenance Program
1.3.b	CRP G2	Operation Experience	InService	Working According to Specifications	Maintained	Good	NO	Normal Maintenance	Life Extension	NO	Include in Maintenance Program
2	Fire Water Pump Container										
2.1	Pump	Operation Experience	InService	Working According to Specifications	Maintained	Average - Further Inspection to be Defined	NO	Full Overhaul	Life Extension	YES	Include in Maintenance Program
2.2	Diesel Engine	Operation Experience	InService	Working According to Specifications	Maintained	Good	NO	Full Overhaul	Life Extension	NO	Include in Maintenance Program
2.3	Generator	Operation Experience	InService	Working According to Specifications	Maintained	Good	NO	Full Overhaul	Life Extension	NO	Include in Maintenance Program
2.4	HVAC	Operation Experience	InService	Working According to Specifications	Maintained	Good	NO	Inspect and replace as required	Life Extension	NO	Include in Maintenance Program
3	Surge Damping Tank	Operation Experience	InService	Working According to Specifications	Maintained	Good	NO	Refurbishments if required	Life Extension	NO	Include in Maintenance Program
4	Air Evacuation System	Operation Experience	InService	Working According to Specifications	Maintained	Good	NO	Refurbishments if required	Life Extension	NO	Include in Maintenance Program
5	Sprinkles	Operation Experience	InService	Working According to Specifications	Maintained	Good	NO	Refurbishments if required	Life Extension	NO	Include in Maintenance Program
6	Valves	Operation Experience	InService	Working According to Specifications	Maintained	Bad	NO	Refurbishments if required	Life Extension	NO	Include in Maintenance Program
7	Fire Hawsers	Operation Experience	InService	Working According to Specifications	Maintained	Good	NO	Refurbishments if required	Life Extension	NO	Include in Maintenance Program

Figure 5.10: Firefighting System Qualitative Condition.

Qualitative Model - Distribution and Deluge System

The firewater fluid is assumed to be seawater in all the piping system, hence a corrosion rate of 0.13 mm/year is used. The external corrosion rate is the same used for the external areas of the hull in the structural analysis, 0.51 mm/year - the same value is used for all regions (accommodation, machinery room and control room).

For the firefighting piping system, coating is present both internally and externally. As stated before, and as the fluid type is seawater, a corrosion allowance of 3 mm is defined. It is also assumed that the criteria for pipe replacement is the corrosion allowance. Thus, the model returns an useful life of 12 years for all firewater pipes. This happened because the rates are equal, the systems has similar dimensions and the corrosion effects are forecasted in the same way, hence the corroded values are very similar. As the operating life is 15 years, the pipes were replaced in 12 years, thus they all have 9 years of useful life left. Therefore, replacement is predicted only in the end of life extension period.

Firefighting System Piping									
Location	**Piping Group ID**	**d (mm)**	**t (mm)**	**c (mm)**	**Ext C (mm/year)**	**Int C (mm/year)**	**Useful Life (Years)**	**Number of Replacements**	**RUL**
Accomodation	APG 1	65.00	5.16	3.00	0.51	0.13	12	1	9
Accomodation	APG 2	80.00	5.49	3.00	0.51	0.13	12	1	9
Accomodation	APG 3	90.00	5.74	3.00	0.51	0.13	12	1	9
Machinery Room	MRPG 1	80.00	5.49	3.00	0.51	0.13	12	1	9
Machinery Room	MRPG 2	90.00	5.74	3.00	0.51	0.13	12	1	9
Machinery Room	MRPG 3	100.00	6.02	3.00	0.51	0.13	12	1	9
Machinery Room	MRPG 4	125.00	6.55	3.00	0.51	0.13	12	1	9
Control Room	CRP G1	65.00	5.16	3.00	0.51	0.13	12	1	9
Control Room	CRP G2	80.00	5.49	3.00	0.51	0.13	12	1	9

Table 5.4: Firewater Piping RUL.

Risk Analysis and Risk Mitigation

The assessments made before for the firefighting system shows that only two subsystem are in a condition different than good. Hence, those are the ones to present higher risks. For the pipes, the mindset for the risk assessment is that as they were replaced 3 years ago, the likelihood of the pipes not performing accordingly is very unlikely. However, the consequences are bad as this means fire would not be contained in a specific region of the unit.

The accommodation area is the location with more people, hence if a fire was to happen there the casualties could be higher than in the machinery or control room. The consequences for the accommodation is then set to 5, and the other areas a value of 4 was selected. All the pipes risk are found to be in ALARP region, and with the low likelihoods, no mitigation is needed for pipes.

The pump has barely been used and the real condition is not known. Thus, the likelihood of the components being degraded is set to a value of 3 - possible. If the pump fails, the consequences are catastrophic, as it would not supply any water to the firefighting system leading to loss of life and property. This resulted into a risk of 15, hence a mitigating action is required here.

Some valves are not performing well and could also cause major consequences depending on the areas they are located. A likelihood of 3 (Possible) and a consequence of 4 (Major) were assigned, and a risk of 12 was found which is in the intolerable area. The remaining systems have risks in the ALARP or tolerable region, and no mitigation is required based on their condition. The full assessment is available on Appendix C.3 - Firefighting Analysis, and Figure 5.11 presents the risk analysis for the accommodation pipes, pump and valves.

The first mitigation to be proposed considers the pump. As the unknown condition is driving the likelihood, the mitigation action should focus on getting a better status in the system condition and fixing the required issues. If this is done, then the pump reliability can be restored and the likelihood of failure is decreased to 1 - unlikely failure event. This reduces the risk from 15 to 5, as the consequence remains the same.

Lastly, a mitigation is proposed for the valves. Although the risk is within ALARP region, it is decided to mitigate it due to the quantity of problematic systems. All valves that require replacement shall be replaced, hence a likelihood of failure is decreased to 1 and a total risk of 4 is found. Figure 5.12 summarizes the analysis.

System		Functionality Description		Failure Description			Failure Effects			Risk		
REF	System/Subsystem/Element	Function	Life Extension Assessment Outcome	Failure Cause or Mechanism	Failure Mode	Detection of Failure	Local Effects	Global Effect	Consequences	L	S	R
1	Deluge and Distribution System											
1.1	Accom.											
1.1.a	APG 1	To transport fresh water into the specific location	Good condition - Pipe has just been replaced and RUL=11 years, i.e. longer than LE period	Corrosion	Corroded pipe can break down	Inspection with non-destructive methods	One section of the pipe breakdowns and stops working	Fire not coantained in accommodation block	Fire in the accommodation block	1	5	5
1.1.b	APG 2	To transport fresh water into the specific location	Good condition - Pipe has just been replaced and RUL=11 years, i.e. longer than LE period	Corrosion	Corroded pipe can break down	Inspection with non-destructive methods	One section of the pipe breakdowns and stops working	Fire not coantained in accommodation block	Fire in the accommodation block	1	5	5
1.1.c	APG 3	To transport fresh water into the specific location	Good condition - Pipe has just been replaced and RUL=11 years, i.e. longer than LE period	Corrosion	Corroded pipe can break down	Inspection with non-destructive methods	One section of the pipe breakdowns and stops working	Fire not coantained in accommodation block	Fire in the accommodation block	1	5	5
2	Fire Water Pump											
2.1	Pump	To pump freshwater into the firefighting pipes	This pump has an average and has barely been used. Although it is maintained, the real condition is unknown.	Lack of maintenance	Components can be worn out if not properly maintained or substituted	Regular Inspection	Pump not working	Pump does not provide fluid to one region in the unit	Fire not contained	3	5	15
6	Valves	To allow/close water passage	Around 10 valves of the entire system are in really bad condition	Time Deterioration and Lack of Replacemment	Components not working properly	Regular Inspection	Valves not opening/closing in one pipe section	Fluid not flowing or flowing too much into a specific region	Fire not contained	3	4	12

Figure 5.11: Risk Analysis Firefighting System.

System		Risk			Risk Mitigation				
REF	System/Subsystem/Element	L	S	R	Mitigation Action	LM	SM	MR	Risk Redunction
2	Fire Water Pump Container								
2.1	Pump	3	5	15	Peform a full overhaul/inspection and replace all the pieces that are in bad condition.	1	5	5	0.67
6	Valves	3	4	12	Replace all the valves that are required-	1	4	4	0.67

Figure 5.12: Risk Mitigation Firefighting System.

5.2.4 Offloading System

The offloading system analysis considers the hose, tanks, pumps and piping systems. A part from the hose, all the other subsystems have quantitative assessments. The following sections describe each analysis performed based on the methodology.

Offloading System Overall Condition

The offloading system condition can be described as average - where some issues are already known and others indicate that inspection is necessary. The offloading hose is currently in bad shape, and requires full replacement to attain compliance during the life extension period.

Cargo tanks are in general OK, with steel renewal work being necessary for the main deck regions. One of the cargo pumps has been running more than the others, and has presented issues such as high noise and overheating - even though it has been maintained.

Some of the pipes were just replaced, hence no major issues are found currently. However, an inspection should be done in order to prove the condition and attain compliance. The qualitative results for the offloading system can be found on Figure 5.13.

ID	ELEMENT	INFORMATION SOURCE	USAGE	USAGE STATUS	MAINTENANCE	CONDITION	OBSOLETE	EXPECTED SCOPE	TYPE OF WORK	CRITICAL SPARE PARTS	SCOPE LOCATION
1	Offloading Hose										
1.1	DC-H Type Yokahoma	Operation Experience	InService	Working According to Specifications	Maintained	Bad	YES	Replace offloading hose	Life Extension	No	Include in Maintenance Program
2	Cargo Tanks										
2.1	Port Cargo Tanks	Operation Experience	InService	Working According to Specifications	Maintained	Average - Known Status of the System	NO	Regions within requirements need to be recoated, and the anodes need to be replaced. Deck Plate requires steel renewal work	Renewal	NO	Include in Maintenance Program
2.2	Central Cargo Tanks	Operation Experience	InService	Working According to Specifications	Maintained	Average - Known Status of the System	NO	Regions within requirements need to be recoated, and the anodes need to be replaced. Deck Plate requires steel renewal work	Renewal	NO	Include in Maintenance Program
2.3	Starboard Cargo Tanks	Operation Experience	InService	Working According to Specifications	Maintained	Average - Known Status of the System	NO	Regions within requirements need to be recoated, and the anodes need to be replaced. Deck Plate requires steel renewal work	Renewal	NO	Include in Maintenance Program
3	Cargo Pumps										
3.1	Eureka CD 400 CP1	Operation Experience	InService	Working According to Specifications	Maintained	Average - Known Status of the System	NO	Overhaul is required during LE period	Life Extension	No	Include in Maintenance Program
3.2	Eureka CD 400 CP2	Operation Experience	InService	Working According to Specifications	Maintained	Average - Known Status of the System	NO	Overhaul is required during LE period	Life Extension	No	Include in Maintenance Program
3.3	Eureka CD 400 CP3	Operation Experience	InService	Working According to Specifications	Maintained	Bad	NO	This pumps has been presenting many issues. A full replacement is suggested instead of common overhaul	Life Extension	No	Include in Maintenance Program
3.4	Eureka CD 400 CP4	Operation Experience	InService	Working According to Specifications	Maintained	Average - Known Status of the System	NO	Overhaul is required during LE period	Life Extension	No	Include in Maintenance Program
3.5	Eureka CD 400 CP5	Operation Experience	InService	Working According to Specifications	Maintained	Good	NO	Auxiliary pump, no major work required	Life Extension	No	Include in Maintenance Program
3.6	Eureka CD 400 CP6	Operation Experience	InService	Working According to Specifications	Maintained	Good	NO	Auxiliary pump, no major work required	Life Extension	No	Include in Maintenance Program
4	Piping System										
4.1	CPG 1	Operation Experience	InService	Working According to Specifications	Maintained	Average - Further Inspection to be Defined	NO	Replacement during LE period	Life Extension	No	Include in Maintenance Program
4.2	CPG 2	Operation Experience	InService	Working According to Specifications	Maintained	Average - Further Inspection to be Defined	NO	Replacement during LE period	Life Extension	No	Include in Maintenance Program

Figure 5.13: Offloading System Overall Condition.

Quantitative Model - Tanks

The cargo tanks analysis follows the same principle as the midship section corrosion assessment. However, the transverse bulkheads are considered, once the tank is a basically a cube. The thickness for plates and stiffeners were assigned based on the midship section drawing available on Appendix A.1 - Structural Components.

There are basically 3 groups of tanks: port, starboard and center tanks. Considering port and starboard tank plates, they are subjected to two different fluids in the side shells: seawater and oil - while the central cargo tanks plates are subject to oil in both sides. For the seawater a rate of 0.13 mm/year (CIMM, 2020) is selected, and 0.1 mm/year for the oil (OCIMF, 1997). The marine atmosphere also affects the external deck plates, with a corrosion rate of 0.51 mm/year (CIMM, 2020). The stiffeners are only corroded by oil, as it is considered they are inside the cargo tanks.

Whether there is coating or not in the tank analysed depends upon its location - 2m below deck level and 2m above baseline are coated. Hence, as the model only analysis the lowest thickness value from a group of values, it predicts the results for coated and uncoated regions. Figure 5.14 and Figure 5.15 presents the expected behaviour of plates and stiffeners for the oil tanks.

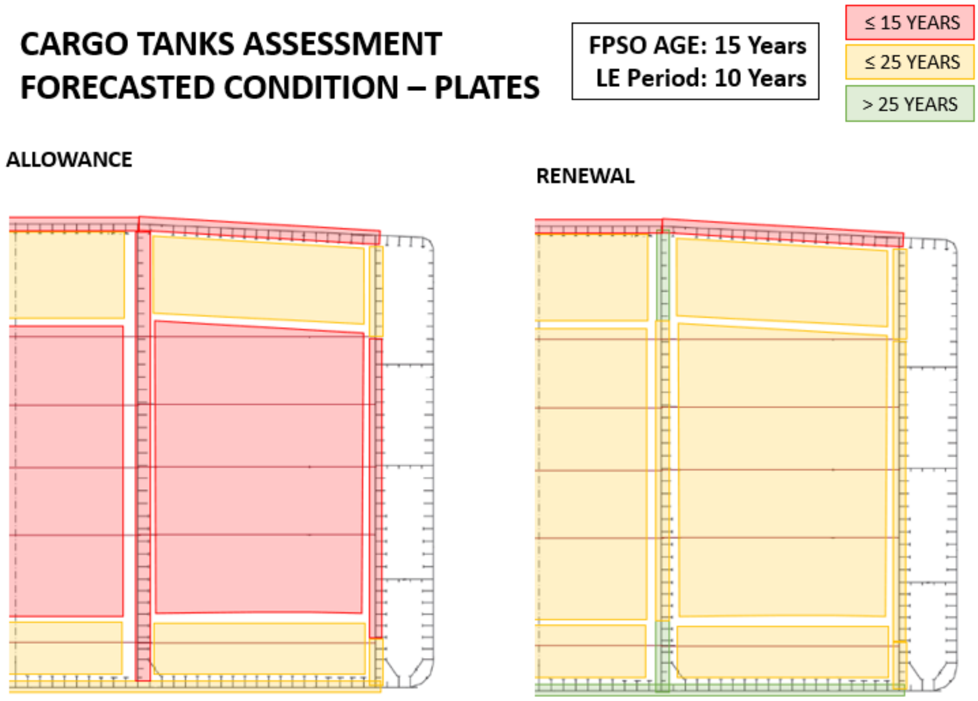


Figure 5.14: Cargo Tanks Plates - Corrosion Forecast.

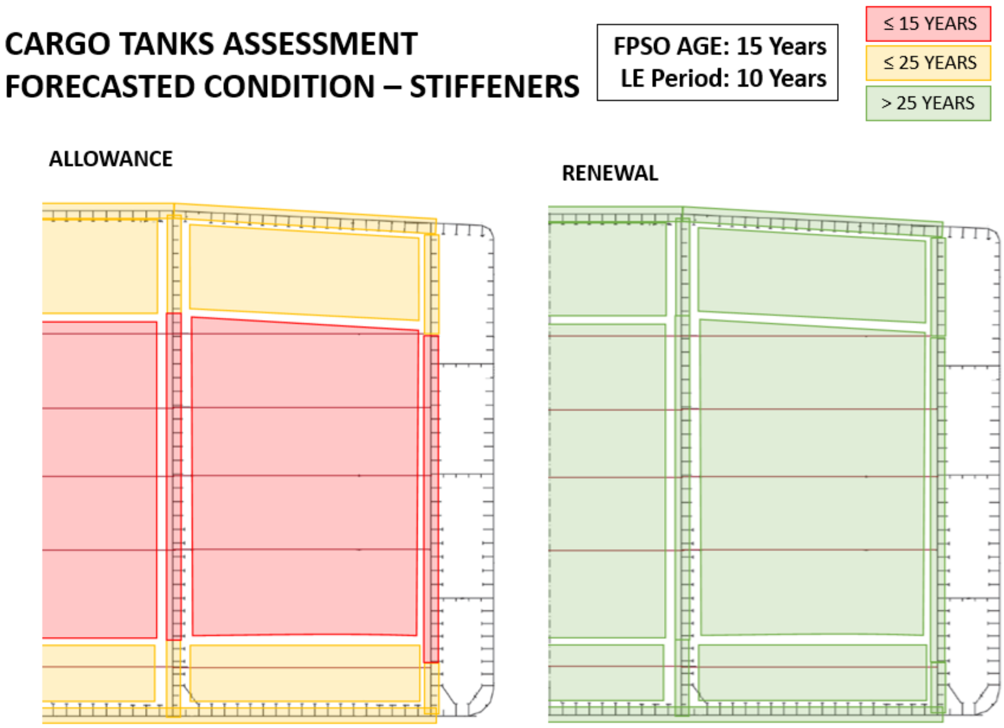


Figure 5.15: Cargo Tanks Stiffeners - Corrosion Forecast.

Quantitative Model - Cargo Piping

As defined before, the cargo pipes have thickness of 7.11mm and 8.18mm. A corrosion rate of 0.025 mm/year is selected to assess the internal corrosion effects - this low rate value is justified based on the effect that internal corrosion in oil pipes are not very concerning, once fluid velocity is low, there is not much oxygen nor erosion particles. The external corrosion rate is assumed to be the atmospheric corrosion of 0.51 mm/year (CIMM, 2020). Coating is assumed both internally and externally.

The analysis resulted in a structural life of 7 years for both pipes, i.e. the time it takes to completely corrode the allowance of 0.3mm for cargo steel plates. Hence, it is assumed that both have been replaced 2 times during the initial operating time and have 6 years left of useful life for the life extension time frame.

Cargo Piping									
Location	Piping Group ID	d (mm)	t (mm)	Ext Corrosion (mm/year)	Int Corrosion (mm/year)	Life (years)	$t_{corroded}$ (mm)	Number of Replacements	RUL
Cargo Tanks	CPG 1	150.00	7.11	0.510	0.025	7	6.74	2	6
Cargo Tanks	CPG 2	200.00	8.18	0.510	0.025	7	7.81	2	6

Table 5.5: Cargo Piping Assessment.

Forecasting the results into the life extension assessment and keeping the same criteria for replacement, the pipes shall be replaced after 6 years of operation. Hence, with a useful life of 7 years, there will only be 1 replacement during the life extension period.

Quantitative Model - Cargo Pumps

The operation profile was defined back in Sections 4.1 and 5.1.3. During the current 15 year of operation, the FPSO has offloaded over 800 times - each offloading taking 24 hours. How much each pump contributed to the offloads was also determined, and this is important to predict the total running hours of each equipment.

The chosen cargo pumps have an overhaul interval defined to be 20.000 hours, hence the results show that - for the assumed operational profile - no pumps have been completely overhauled during the current life span. Besides the auxiliary pumps, the main ones start requiring overhauls after 735 running hours.

Calculating the number of offloads that can be made with the left running hours in each pump, and comparing them with the predict offloading profile, it is seen that two pumps can last without an overhaul for 1 year, while the other two reach the criteria before even 1 year of the life extension period. As these results are pretty low, and keeping the same mindset of up to date maintenance, it is a good idea to perform the overhauls in all main cargo pumps before entering the life extension period. The results are presented on Table 5.6.

AS IS CONDITION							LIFE EXTENSION ASSESSMENT				
Offloading Pumps	**Usage (%) of Each Pump**	**Total Running Hours**	**Overhauls Performed**	**Current Running Hours**	**Hours Until Next Overhaul**	**Number of Offloads until Next Overhaul**	**Year of Required Overhaul**	**Years in Operation during LE**	**Running Hours during LE**	**Total Running Hours**	**Overhaul Required?**
CP 1 (Main)	88	18229.00	0.00	18229.00	1771.00	73.79	2022	1	11021.27	29250.27	YES
CP 2 (Main)	86	17814.70	0.00	17814.70	2185.30	91.05	2022	1	10770.79	28585.49	YES
CP 3 (Main)	93	19264.74	0.00	19264.74	735.26	30.64	2021	0	11647.48	30912.22	YES
CP 4 (Main)	90	18643.29	0.00	18643.29	1356.71	56.53	2021	0	11271.75	29915.05	YES
CP 5 (Redundancy)	21	4350.10	0.00	4350.10	15649.90	652.08	2034	13	2630.08	6980.18	NO
CP 6 (Redundancy)	18	3728.66	0.00	3728.66	16271.34	677.97	2034	13	2254.35	5983.01	NO

Table 5.6: Overhauls Analysis for Offloading Pumps.

Risk Analysis and Risk Mitigation

The results of the life extension assessment for the offloading system are summarized by Table 5.7. For the offloading system, most of the risk analysis consequences of the subsystems focused on postponing or cancelling the offloading process. This had a catastrophic consequence defined as it would highly affect the economical side of operation.

Other consequence identified is related to the offloading hose that can break down and spill oil into the sea, hence another catastrophic risk considering the environmental and reputation impacts. Leakage from cargo tanks could result in vessel heeling that could lead to capsizing, thus defined as a also catastrophic.

However, this assessment is useful for the port and starboard tanks, once they could leak into the ballast areas. For the central cargo tanks, the consequences are lower (defined as moderate), because if leakage was to happen, it would affect the other cargo tanks.

One of the pumps also presented overheating problems that in the worst case scenario could lead to a fire in the pump room spreading to the FPSO. The auxiliary pumps presented risks in negligible areas, hence not much is necessary for them.

REF	System/Subsystem/Element	Life Extension Assessment Outcome
1	Offloading Hoose	
1.1	DC-H Type Yokahoma	The hose condition is bad because it is old, hence should be replaced.
2	Cargo Tanks	
2.1	Port Cargo Tanks	Corrosion Allowance has already been consumed, and steel renewal work is expected during the life extension period. Deck plates are already under the thickness reduction limit for renewal work
2.2	Central Cargo Tanks	Corrosion Allowance has already been consumed, and steel renewal work is expected during the life extension period. Deck plates are already under the thickness reduction limit for renewal work
2.3	Starboard Cargo Tanks	Corrosion Allowance has already been consumed, and steel renewal work is expected during the life extension period. Deck plates are already under the thickness reduction limit for renewal work
3	Cargo Pumps	
	Eureka CD 400 CP1	Pump working good - next overhaul in 1771 running hours
	Eureka CD 400 CP2	Pump working good - next overhaul in 2184 running hours
	Eureka CD 400 CP3	Next overhaul in 735 running hours, but the pump is in bad condition. It is overheating and with vibration and loud noises.
	Eureka CD 400 CP4	Pump working good - next overhaul in 1356 running hours
	Eureka CD 400 CP5	Auxiliary pump, has been used for less than 5000 running hours - no major issues for life extension
	Eureka CD 400 CP6	Auxiliary pump, has been used for less than 4000 running hours - no major issues for life extension
4	Piping System	
4.1	CPG 1	Pipe has been substituted twice during operating life. Next replacement is in 6 years. Rigth now, it is in good condition, no major issues but an inspection is necessary to prove it.
4.2	CPG 2	Pipe has been substituted twice during operating life. Next replacement is in 6 years. Rigth now, it is in good condition, no major issues but an inspection is necessary to prove it.

Table 5.7: Offloading System Life Extension Assessment.

The likelihoods were assigned based on the quantitative outcomes. For instance if a life span was higher than total period in service, the likelihood was set to be between 1 and 2. In the other hand, components that presented life results within life extension period or even below it, had higher likelihood of problems happening. Figure 5.16 presents an overview of the main results, and the complete assessment can be seen in Appendix C.4 - Offloading System Analysis.

Risks in intolerable areas were mitigated, proposing to renewal the sections necessary in the tanks (stiffeners or tanks), and to change the offloading hose to a new one. Regarding the pumps, the mitigation proposes to substitute pump 3 that is overheating and to perform an overhaul before entering the new operation period. The results are presented on Figure 5.17.

System		Functionality Description		Failure Description			Failure Effects			Risk Ranking		
REF	System/Subsystem/ Element	Function	Life Extension Assessment Outcome	Failure Cause or Mechanism	Failure Mode	Detection of Failure	Local Effects	Global Effect	Consequences	L	S	R
1	Offloading Hoose											
1.1	DC-H Type Yokahoma	To transport the produced oil into the shuttle tanker	The hose condition is bad because it is old, hence should be substituted.	Age deteoration	Colapse or break down due to detereoation	Inspection ?	Offloading process has to be postponed/cancelled	Leakage of oil	Pollution to the ocean with cargo oil	4	5	20
2	Cargo Tanks											
2.1	Port Cargo Tanks	To hold the produced oil	Corrosion Allowance has already been consumed, and steel renewal work is expected during the life extension period. Deck plates are already under the thickness reduction limit for renewal work	Steel Corrosion	Cracking of steel plates or stiffeners	Regular Inspection	Cracking and opening in the tank	Oi Spilling into Ballast Tanks	Heeling of the vessel	3	5	15
2.2	Central Cargo Tanks	To hold the produced oil	Corrosion Allowance has already been consumed, and steel renewal work is expected during the life extension period. Deck plates are already under the thickness reduction limit for renewal work	Steel Corrosion	Cracking of steel plates or stiffeners	Regular Inspection	Cracking and opening in the tank	Oi Spilling into other Tanks	Heeling of the vessel	3	3	9
2.3	Starboard Cargo Tanks	To hold the produced oil	Corrosion Allowance has already been consumed, and steel renewal work is expected during the life extension period. Deck plates are already under the thickness reduction limit for renewal work	Steel Corrosion	Cracking of steel plates or stiffeners	Regular Inspection	Cracking and opening in the tank	Oi Spilling into Ballast Tanks	Heeling of the vessel	3	5	15
3	Cargo Pumps	To pump cargo oil in and out the										
	Eureka CD 400 CP1	To pump cargo oil in and out the tanks	Pump working good - next overhaul in 1771 running hours	Diverse failure from components leading to pump not working	Cracking or equipment not working	Overhualing, inspection and proper maintenance	The specific stops working	Overload in the other pumps	Offloading process has to be cancelled/postponed	2	5	10
	Eureka CD 400 CP2	To pump cargo oil in and out the tanks	Pump working good - next overhaul in 2184 running hours	Diverse failure from components leading to pump not working	Cracking or equipment not working	Overhualing, inspection and proper maintenance	The specific stops working	Overload in the other pumps	Offloading process has to be cancelled/postponed	2	5	10
	Eureka CD 400 CP3	To pump cargo oil in and out the tanks	Next overhual in 735 running hours, but the pump is in bad condition. It is overheating and with vibration and loud noises.	Overheating components	Cracking or equipment not working	Overhualing, inspection and proper maintenance	The specific stops working	Fire in the pump room	Offloading process has to be cancelled/postponed/ Fire can spread to the FPSO	4	5	20
	Eureka CD 400 CP4	To pump cargo oil in and out the tanks	Pump working good - next overhaul in 1356 running hours	Diverse failure from components leading to pump not working	Cracking or equipment not working	Overhualing, inspection and proper maintenance	The specific stops working	Overload in the other pumps	Offloading process has to be cancelled/postponed	2	5	10
	Eureka CD 400 CP5	To pump cargo oil in and out the tanks	Auxiliary pump, has been used for less than 5000 running hours - no major issues for life extension	Diverse failure from components leading to pump not working	Cracking or equipment not working	Overhualing, inspection and proper maintenance	The specific stops working	Overload in the other pumps	Offloading process has to be cancelled/postponed	1	3	3
	Eureka CD 400 CP6	To pump cargo oil in and out the tanks	Auxiliary pump, has been used for less than 4000 running hours - no major issues for life extension	Diverse failure from components leading to pump not working	Cracking or equipment not working	Overhualing, inspection and proper maintenance	The specific stops working	Overload in the other pumps	Offloading process has to be cancelled/postponed	1	3	3
4	Piping System	To transport cargo oil										
4.1	CPG 1	To transport cargo oil	Pipe has been substituted twice during operating life. Next replacement is in 6 years. Rigth now, it is in good condition, no major issues but an inspection is necessary to prove it	Steel Corrosion	Cracking of cargo oil pipes	Regular Non-Destructive Inspection	Leakage of oil in one region of the unit	Accummulation of oil outside the cargo tank	Vessel can heel/capsize and Offloading process cancelled/postponed	1	4	4
4.2	CPG 2	To transport cargo oil	Pipe has been substituted twice during operating life. Next replacement is in 6 years. Rigth now, it is in good condition, no major issues but an inspection is necessary to prove it.	Steel Corrosion	Cracking of cargo oil pipes	Regular Non-Destructive Inspection	Leakage of oil in one region of the unit	Accummulation of oil outside the cargo tank	Vessel can heel/capsize and Offloading process cancelled/postponed	1	4	4

Figure 5.16: Offloading System Risk Analysis.

System		Functionality Description		Risk Ranking			Risk Mitigation				
REF	**System/Subsystem/ Element**	**Function**	**Life Extension Assessment Outcome**	**L**	**S**	**R**	**Mitigation Action**	**LM**	**SM**	**MR**	**Dif**
1	Offloading Hoose										
1.1	DC-H Type Yokahoma	To transport the produced oil into the shuttle tanker	The hose condition is bad because it is old, hence should be substituted.	4	5	20	Completely substitute the offloading hose to a new one	1	5	5	0.75
2	Cargo Tanks										
2.1	Port Cargo Tanks	To hold the produced oil	Corrosion Allowance has already been consumed, and steel renewal work is expected during the life extension period. Deck plates are already under the thickness reduction limit for renewal work	3	5	15	Perform renewal work into the necessary areas	1	5	5	0.6667
2.2	Central Cargo Tanks	To hold the produced oil	Corrosion Allowance has already been consumed, and steel renewal work is expected during the life extension period. Deck plates are already under the thickness reduction limit for renewal work	3	3	9	Perform renewal work into the necessary areas	1	3	3	0.6667
2.3	Starboard Cargo Tanks	To hold the produced oil	Corrosion Allowance has already been consumed, and steel renewal work is expected during the life extension period. Deck plates are already under the thickness reduction limit for renewal work	3	5	15	Perform renewal work into the necessary areas	1	5	5	0.6667
3	Cargo Pumps	To pump cargo oil in and out the									
	Eureka CD 400 CP1	To pump cargo oil in and out the tanks	Pump working good - next overhaul in 1771 running hours	2	5	10	Overhaul the pump before entering the LE period, even with little time run since last overhaul	1	5	5	0.5
	Eureka CD 400 CP2	To pump cargo oil in and out the tanks	Pump working good - next overhaul in 2184 running hours	2	5	10	Overhaul the pump before entering the LE period, even with little time run since last overhaul	1	5	5	0.5
	Eureka CD 400 CP3	To pump cargo oil in and out the tanks	Next overhual in 735 running hours, but the pump is in bad condition. It is overheating and with vibration and loud noises.	4	5	20	Change for a new pump	1	5	5	0.75
	Eureka CD 400 CP4	To pump cargo oil in and out the tanks	Pump working good - next overhaul in 1356 running hours	2	5	10	Overhaul the pump before entering the LE period, even with little time run since last overhaul	1	5	5	0.5

Figure 5.17: Offloading System Mitigation Actions.

5.2.5 Power Generation System

The power generation system is analysed considering the selected main engines and the assumed operation profile. The quantitative model developed considered the time for component replacement and overhauls to be performed, while the distribution system is studied considering the corrosion effects.

Power Generation System Overall Condition

The power generation system overall condition varies from average to good. Some systems, such as the main engines are in average condition as they have been running since the start of operation. It is expected that some of their components have been degraded overtime and need replacement, as well as overhauls. The tanks have not been maintained and might need replacement.

Fuel transfer pipes have been replaced 3 years ago, hence do not present any issues. The generators are also in good condition and not much work is expected during the life extension period. The results are presented on Figure 5.18.

ID	ELEMENT	INFORMATION SOURCE	USAGE	USAGE STATUS	MAINTENANCE	CONDITION	OBSOLETE	EXPECTED SCOPE	TYPE OF WORK	CRITICAL SPARE PARTS	SCOPE LOCATION
1	Main Engines										
1.1	Wartsila 46DF Engine 01	Maintenance Software	InService	Working According to Specifications	Maintained	Average - Known Status of the System	NO	Some components require overhaul and replacement before life extension, while other will require during	Life Extension	NO	Included in Maintenance Program
1.2	Wartsila 46DF Engine 02	Maintenance Software	InService	Working According to Specifications	Maintained	Average - Known Status of the System	NO	Some components require overhaul and replacement before life extension, while other will require during	Life Extension	NO	Included in Maintenance Program
1.3	Wartsila 46DF Engine 03	Maintenance Software	InService	Working According to Specifications	Maintained	Average - Known Status of the System	NO	Some components require overhaul and replacement before life extension, while other will require during	Life Extension	NO	Included in Maintenance Program
1.4	Wartsila 46DF Engine 04	Maintenance Software	InService	Working According to Specifications	Maintained	Average - Known Status of the System	NO	Some components require overhaul and replacement before life extension, while other will require during	Life Extension	NO	Included in Maintenance Program
1.5	Wartsila 46DF Engine 05	Maintenance Software	InService	Working According to Specifications	Maintained	Average - Known Status of the System	NO	Some components require overhaul and replacement before life extension, while other will require during	Life Extension	NO	Included in Maintenance Program
1.6	Wartsila 46DF Engine 06	Maintenance Software	InService	Working According to Specifications	Maintained	Average - Known Status of the System	NO	Some components require overhaul and replacement before life extension, while other will require during	Life Extension	NO	Included in Maintenance Program
1.7	Wartsila 46DF Engine 07	Maintenance Software	InService	Working According to Specifications	Maintained	Good	NO	No major work necessary, just regular maintenance	Life Extension	NO	Included in Maintenance
1.8	Wartsila 46DF Engine 08	Maintenance Software	InService	Working According to Specifications	Maintained	Good	NO	No major work necessary, just regular maintenance	Life Extension	NO	Included in Maintenance
2	Emergency										
2.1	Wartsila 20 Emergency Engine 01	Maintenance Software	InService	Working According to Specifications	Maintained	Good	NO	No major work necessary, just regular maintenance	Life Extension	NO	Included in Maintenance Program
2.2	Wartsila 20 Emergency Engine 02	Maintenance Software	InService	Working According to Specifications	Maintained	Good	NO	No major work necessary, just regular maintenance	Life Extension	NO	Included in Maintenance Program
2.3	Wartsila 20 Emergency Engine 03	Maintenance Software	InService	Working According to Specifications	Maintained	Good	NO	No major work necessary, just regular maintenance	Life Extension	NO	Included in Maintenance Program
3	Distribution System										
3.1	FP G01	Operation Experience	InService	Working According to Specifications	Maintained	Good	NO	Might be necessary to replace the pipes during LE period	Renewal	NO	Offshore Campaign Requiring
3.2	FP G02	Operation Experience	InService	Working According to Specifications	Maintained	Good	NO	Might be necessary to replace the pipes during LE period	Renewal	NO	Offshore Campaign Requiring
4	Diesel Tank										
4.1	Fuel Tank 01	Operation Experience	InService	Working According to Specifications	Not Maintained	Average - Further Inspection to be	NO	Steel renewal work in necessary areas	Renewal	No	Yard Stay
4.2	Fuel Tank 02	Operation Experience	InService	Working According to Specifications	Not Maintained	Average - Further Inspection to be	NO	Steel renewal work in necessary areas	Renewal	No	Yard Stay

Figure 5.18: Power Generation System Condition.

Quantitative Model - Engines and Generators

Based on the power generating profile and engine's usage defined before, it is possible to calculate what is the running hours associated with each element, as presented in Table 5.8.

Main Power System - Operating Profile					
Wartsila 46DF	**Usage (%)**	**Current Running Hours**	**Life Extension Factor**	**Life Extension Running Hours**	**Total Hours**
Engine 1 (Main)	80	99864.00	80.00	66576.00	166440.00
Engine 2 (Main)	85	106105.50	85.00	70737.00	176842.50
Engine 3 (Main)	81	101112.30	81.00	67408.20	168520.50
Engine 4 (Main)	92	114843.60	92.00	76562.40	191406.00
Engine 5 (Main)	88	109850.40	88.00	73233.60	183084.00
Engine 6 (Main)	91	113595.30	91.00	75730.20	189325.50
Engine 6 (Aux)	21	26214.30	21.00	17476.20	43690.50
Engine 6 (Aux)	26	32455.80	26.00	21637.20	54093.00
Wartsila 20	**Usage (%)**	**Current Running Hours**	**Life Extension Factor**	**Life Extension Running Hours**	**Total Hours**
Generator 1	20	2628.00	20.00	1752.00	4380.00
Generator 2	15	1971.00	15.00	1314.00	3285.00
Generator 3	13	1708.20	13.00	1138.80	2847.00

Table 5.8: Running Hours for each Element of Main Power Generation System.

For this FPSO, all the main engines are the same. Hence, although each engine is composed by a set of different subsystems, and each with its own time between overhauls and expected life, they are the same for all the engines. Therefore, the results presented in this section are only for the engine with longer running hours (Engine 4). The full assessment is found in Appendix C.5 - Power Generation System.

When analysing the overhauls and replacements performed in the engine, it is assumed that all the timelines proposed by the vendor are followed. Hence, all components were overhauled and replaced within the defined time frame if it was required. With that information, it is possible to predict what is the remaining running hours left before a new overhaul or replacement is required.

The analysis for Engine 4 is presented in Table 5.9. It can be seen that there were some overhauls performed already, a part for the inlet valve. For the replacements, all components have been replaced at least once, except for the cylinder liner. Similar results are found for all the other engines and generator.

WARTSILE 46DF - ENGINE 4	Information		Overhaul		Replacements	
	Overhaul Interval (Running Hours)	Expected Life Time (Running Hours)	Overhauls Performed	Remaining Time for Next Overhaul	Replacements Performed	Remaining Hours for Next Replacement
Big End Bearing	16000	36000	7	13156.4	3	29156.4
Cylinder Head	16000	60000	7	13156.4	1	5156.4
Cylinder Liner	16000	180000	7	13156.4	0	65156.4
Exhaust Valve	15000	15000	7	5156.4	7	5156.4
Injection Nozzles	8000	8000	14	5156.4	14	5156.4
Injection Pump (Twin Pump)	12000	24000	9	5156.4	4	5156.4
Injection Pump, Pilot	24000	24000	4	5156.4	4	5156.4
Inlet Valve	150000	24000	0	35156.4	4	5156.4
Main Bearing	24000	36000	4	5156.4	3	29156.4
Piston	24000	36000	4	5156.4	3	29156.4
Piston Rings	16000	16000	7	13156.4	7	13156.4

Table 5.9: Overhauls and Replacements performed in Engine 4.

This information allows for the decision of when the next overhaul and replacement shall be performed - do it all before, do everything during, or do some before and some after the life extension period. If one is to perform all replacements and overhauls before entering the life extension period in Engine 4, 45 overhauls and 34 replacements will be required during the life extension period (for all components in the engine).

Considering that no work is performed before entering the period of extension, the engine components will require 46 overhauls and 36 replacements. However, this is not such an uniform decision, as it requires to shut down the engine for the inspection services to take place. Many components have the same overhauling period as well, what means it can be carried out in parallel minimizing the costs and time in standby.

Hence, an analysis on what components shall be carried out before and during the life extension period is the best option to find an optimum decision. For this study, it is decided that any component that has running life lower than 10 % of the total life extension running hours, shall have an overhaul or replacement performed. For Engine 4, the results of this assessment are as follows:

Engine 4 - Overhaul and Replace Some all with life less 0.1*Life Extension Period				
Overhauls	**Overhaul before LE?**	**Remaining Hours for Next Overhaul**	**Number of Overhauls During LE**	**Hours left Running without Overhaul**
Big End Bearing	NO	13156.40	4	15406.00
Cylinder Head	NO	13156.40	4	15406.00
Cylinder Liner	NO	13156.40	4	15406.00
Exhaust Valve	YES	15000.00	5	1562.40
Injection Nozzles	YES	8000.00	9	4562.40
Injection Pump (Twin Pump)	YES	12000.00	6	4562.40
Injection Pump, Pilot	YES	24000.00	3	4562.40
Inlet Valve	NO	35156.40	1	41406.00
Main Bearing	YES	24000.00	3	4562.40
Piston	YES	24000.00	3	4562.40
Piston Rings	YES	16000.00	4	12562.40
			46	
Replacements	**Replace before LE?**	**Remaining Hours for Next Replacement**	**Number of Replacements During LE**	**Hours Left Running without Replacement**
Big End Bearing	NO	29156.40	2	11406.00
Cylinder Head	YES	5156.40	1	16562.40
Cylinder Liner	NO	65156.40	1	11406.00
Exhaust Valve	YES	15000.00	5	1562.40
Injection Nozzles	YES	8000.00	9	4562.40
Injection Pump (Twin Pump)	YES	24000.00	3	4562.40
Injection Pump, Pilot	YES	24000.00	3	4562.40
Inlet Valve	YES	5156.40	3	4562.40
Main Bearing	NO	36000.00	2	11406.00
Piston	NO	36000.00	2	11406.00
Piston Rings	NO	16000.00	4	15406.00
			35	

Table 5.10: Overhauling and Replacements - Before and During Life Extension Period.

Quantitative Model - Fuel Tank

The corrosion rate for heavy fuel is based on a study from Špiro Ivošević et al. (2019), where the author presents a probabilistic approach to estimate corrosion rates of fuel tanks in bulk carriers. Two sets of components are studied - inner bottom plates and side watertight girder. Using the same approach for coating as presented in the analysis for structural systems and cargo tanks, and selecting the summary value from all the analysis made for the inner bottom plates, a value of 0.156 mm/year is chosen. The same value is kept for all plates and stiffeners, due to lack of other information available.

The corrosion allowance is set to be 3 mm and thickness renewal is defined according to guidelines - both were previously presented in Section 3.4.1. The external corrosion on the fuel tanks is also the marine atmospheric corrosion, with a value of 0.51 mm/year. The tanks are assumed to be coated, both internally and externally.

For these assumptions, the cargo tanks plates have the corrosion allowance consumed in 12 years, while the requirements for steel renewal works ranges from 12 to 15 years. The stiffeners presented results slightly better, as they are only subjected to internal corrosion of the fuel. The corrosion allowance is consumed within 20 years, while steel renewal work is needed in 20 and 25 years. Both results are presented on Table 5.11

FUEL TANK - PLATES											
ID	Side	t_{gross} (mm)	Corrosion Allowance (mm)	K	$t_{renewal}$ (mm)	Internal Corrosion Rate (mm/year)	Internal Coating?	External Corrosion Rate (mm/year)	External Coating?	RUL Allowance (years)	RUL Renewal (years)
PCT 1	1 (Transverse Bulkhead)	17.50	3	0.75	13.13	0.156	YES	0.51	YES	12	13
PCT 1	2 (Deck Shell)	30.00	3	0.80	24.00	0.156	YES	0.51	YES	12	14
PCT 1	3 (Longitudinal/Side Shell)	17.50	3	0.80	14.00	0.156	YES	0.51	YES	12	12
PCT 1	4 (Bottom Shell)	31.00	3	0.80	24.80	0.156	YES	0.51	YES	12	15
PCT 1	5 (Transverse Bulkhead)	17.50	3	0.75	13.13	0.156	YES	0.51	YES	12	13
PCT 1	6 (Longitudinal(Side Shell)	17.50	3	0.80	14.00	0.156	YES	0.51	YES	12	12
FUEL TANK - PLATES											
ID	Side	t_{gross} (mm)	Corrosion Allowance (mm)	K	$t_{renewal}$ (mm)	Internal Corrosion Rate (mm/year)	Internal Coating?	External Corrosion Rate (mm/year)	External Coating?	RUL Allowance (years)	RUL Renewal (years)
PCT 1	1 (Transverse Bulkhead)	12.00	3	0.75	9.00	0.156	YES	0	-	20	20
PCT 1	2 (Deck Shell)	15.00	3	0.75	11.25	0.156	YES	0	-	20	25
PCT 1	3 (Longitudinal/Side Shell)	12.00	3	0.75	9.00	0.156	YES	0	-	20	20
PCT 1	4 (Bottom Shell)	15.00	3	0.75	11.25	0.156	YES	0	-	20	25
PCT 1	5 (Transverse Bulkhead)	12.00	3	0.75	9.00	0.156	YES	0	-	20	20
PCT 1	6 (Longitudinal(Side Shell)	12.00	3	0.75	9.00	0.156	YES	0	-	20	20

Table 5.11: Life Spans of Corrosion Allowance Consumption and Steel Renewal Criteria for Fuel Tank.

Qualitative Model - Fuel Pipes

For the fuel piping system, a corrosion allowance of 2 mm is defined, as presented in Section 3.4.1. The thickness dimensions were presented before, and the criteria to predict useful life is corrosion allowance being consumed in a specific time frame. For the fuel pipes, the same external corrosion rate of 0.51 mm/year as for the other systems is selected, and the pipe is considered coated. The internal rate is defined as 0.156 mm/year, and the pipe is also coated internally.

The results are presented on Table 5.11, it is seen that the model forecasted that it takes 12 years for the corrosion allowance in the fuel pipes to be completely wasted. Hence, keeping the best scenario in mind, it is assumed that both were replaced after 12 years, and now that the operation has reached 15 years, they have 9 years of useful operation left.

Fuel Pipes												
Location	**Piping Group ID**	**d (mm)**	**t (mm)**	**c (mm)**	**Ext Corrosion (mm/year)**	**External Coating?**	**Internal Corrosion (mm/year)**	**Internal Coating?**	**Life (years)**	$t_{corroded}$ **(mm)**	**Number of Replacements**	**RUL**
Cargo Tanks	CPG 1	114.30	6.00	2.00	0.51	YES	0.156	YES	12	3.30	1	9
Cargo Tanks	CPG 2	139.80	8.50	2.00	0.51	YES	0.156	YES	12	4.69	1	9

Table 5.12: Fuel Piping Corrosion Prediction.

Risk Analysis and Risk Mitigation

The power system analysis starts by gathering all the information on life extension and then analysing what would happen if the current condition is kept. Table 5.13 presents an overview of the assessment and Figure 5.19 presents the results for the risk analysis.

As many subsystem have the same outcomes, it was decided to present only one result. For example, although the engines have different time frames for replacements and overhauls, the overall assessment is the same - some components need overhauls and replacement, while others don't. The same mentality is kept to the other systems.

One can see that the higher risk relies on not doing the necessary work to establish a good condition into the subsystems. Therefore, the mitigation action is common to all the high risk system - perform the necessary work to lower the likelihood of something going wrong. For the engines, the mitigation action is to perform the overhauls and replacements into the components that need it, while for the fuel tanks is to renew the steel or completely replace it. The auxiliary engines, emergency generators and distribution risk do not need any mitigation action. The mitigated risks are presented in Figure 5.22.

REF	System/Subsystem/Element	Life Extension Assessment Outcome
1	Main Engines	
1.1	Wartsila 46DF Engine 01	Some components require overhaul and replacement before life extension, while others will require during
1.2	Wartsila 46DF Engine 02	Some components require overhaul and replacement before life extension, while others will require during
1.3	Wartsila 46DF Engine 03	Some components require overhaul and replacement before life extension, while others will require during
1.4	Wartsila 46DF Engine 04	Some components require overhaul and replacement before life extension, while others will require during
1.5	Wartsila 46DF Engine 05	Some components require overhaul and replacement before life extension, while others will require during
1.6	Wartsila 46DF Engine 06	Some components require overhaul and replacement before life extension, while others will require during
1.7	Wartsila 46DF Engine 07	Some components require overhaul and replacement before life extension, while others will require during
1.8	Wartsila 46DF Engine 08	Some components require overhaul and replacement before life extension, while others will require during
2	Emergency Power	
2.1	Wartsila 20 Emergency Engine 01	Emergency generators are in overall good condition and only regular maintenance is expected
2.2	Wartsila 20 Emergency Engine 02	Emergency generators are in overall good condition and only regular maintenance is expected
2.3	Wartsila 20 Emergency Engine 03	Emergency generators are in overall good condition and only regular maintenance is expected
3	Distribution System	
3.1	FP G01	Pipes have been replaced 3 years ago, and next replacement is expected within 9 years of life extension operation
3.2	FP G02	Pipes have been replaced 3 years ago, and next replacement is expected within 9 years of life extension operation
4	Diesel Tank	
4.1	Fuel Tank 01	The tank plates are not maintained and the forecasted condition shows that they need to be replaced before life extension period
4.2	Fuel Tank 02	The tank plates are not maintained and the forecasted condition shows that they need to be replaced before life extension period

Table 5.13: Power Systems Life Extension Assessment.

System		Functionality Description		Failure Description			Failure Effects			Risk Ranking		
REF	**System/Subsystem/Element**	**Function**	**Life Extension Assessment Outcome**	**Failure Cause or Mechanism**	**Failure Mode**	**Detection of Failure**	**Local Effects**	**Global Effect**	**Consequences**	**L**	**S**	**R**
1	Main Engines											0
1.1	Wartsila 46DF Engine 01	To provide power for the FPSO systems	Some components require overhaul and replacement before life extension, while other will require during	Diverse failure from components leading to pump not working	Cracking or equipment not working	Regular Inspection	The specific engine stops working	No/low power provided to the FPSO	Production has to be stopped	3	5	15
1.7	Wartsila 46DF Engine 07	To provide power for the FPSO systems	Some components require overhaul and replacement before life extension, while other will require during	Diverse failure from components leading to pump not working	Cracking or equipment not working	Regular Inspection	The specific engine stops working	No/low power provided to the FPSO	Production has to be stopped	1	3	3
1.8	Wartsila 46DF Engine 08	To provide power for the FPSO systems	Some components require overhaul and replacement before life extension, while other will require during	Diverse failure from components leading to pump not working	Cracking or equipment not working	Regular Inspection	The specific engine stops working	No/low power provided to the FPSO	Production has to be stopped	1	3	3
2	Emergency											0
2.1	Wartsila 20 Emergency Engine 01	To provide emergency power when needed	Emergency generators are in overall good condition and only regular maintenance is expected	Diverse failure from components leading to pump not working	Cracking or equipment not working	Regular Inspection	The specific emergency generator stops working	No/low emergency power provided to the FPSO	Production has to be stopped	1	5	5
3	Distribution											0
3.1	FP G01	To provide fuel to the energy systems	Pipes have been replaced 3 years ago, and next replacement is expected within 9 years of life extension operation	Steel Corrosion	Cracking of pipes	Regular Non-Destructive Inspection	Leakage of fuel inside the machienry room	No fuel provided to the engines	No power generate in the Unit	1	5	5
4	Diesel Tank											0
4.1	Fuel Tank 01	To store the fuel used in the power generation	The tank plates are not maintained and the forecasted condition shows that they need to be replaced before life extension period	Steel Corrosion	Breakdown of the fuel tank	Regular Inspection	One section of the fuel tank breaks down and fuel leaks into the machinery room	Structural Colapse and no place to store fuel	No power generate in the Unit	4	5	20

Figure 5.19: Power Generation System Risk Analysis.

System		Functionality Description	Risk Ranking			Risk Mitigation				
REF	**System/Subsystem/Element**	**Life Extension Assessment Outcome**	**L**	**S**	**R**	**Mitigation Action**	**LM**	**SM**	**MR**	**Dif**
1	Main Engines									
1.1	Wartsila 46DF Engine 01	Some components require overhaul and replacement before life extension, while other will require during	3	5	15	Overhaul and Replace all the necessary components before entering the life extension period, and then follow the inspection interval correctly,	1	5	5	0.6667
1.2	Wartsila 46DF Engine 02	Some components require overhaul and replacement before life extension, while other will require during	3	5	15	Overhaul and Replace all the necessary components before entering the life extension period, and then follow the inspection interval correctly,	1	5	5	0.6667
1.3	Wartsila 46DF Engine 03	Some components require overhaul and replacement before life extension, while other will require during	3	5	15	Overhaul and Replace all the necessary components before entering the life extension period, and then follow the inspection interval correctly,	1	5	5	0.6667
1.4	Wartsila 46DF Engine 04	Some components require overhaul and replacement before life extension, while other will require during	3	5	15	Overhaul and Replace all the necessary components before entering the life extension period, and then follow the inspection interval correctly,	1	5	5	0.6667
1.5	Wartsila 46DF Engine 05	Some components require overhaul and replacement before life extension, while other will require during	3	5	15	Overhaul and Replace all the necessary components before entering the life extension period, and then follow the inspection interval correctly,	1	5	5	0.6667
1.6	Wartsila 46DF Engine 06	Some components require overhaul and replacement before life extension, while other will require during	3	5	15	Overhaul and Replace all the necessary components before entering the life extension period, and then follow the inspection interval correctly,	1	5	5	0.6667
4	Diesel Tank									
4.1	Fuel Tank 01	The tank plates are not maintained and the forecasted condition shows that they need to be replaced before life extension period	4	5	20	Replace the tanks for new ones or renew the steel plates	1	5	5	0.75
4.2	Fuel Tank 02	The tank plates are not maintained and the forecasted condition shows that they need to be replaced before life extension period	4	5	20	Replace the tanks for new ones or renew the steel plates	1	5	5	0.75

Figure 5.20: Power Generation Mitigation Actions.

5.2.6 Telecommunication and Control Systems

To define the condition of the electronic systems, a workshop was performed with an experienced electrical, instrumentation, control and telecommunication engineer at Altera Infrastructure. The mindset was to predict what could possibly be the condition of the systems after 15 years of operation and during life extension period.

Electronic Systems Overall Condition

The analysis starts by defining a condition to the automation systems - it is assumed that their design life is around 15 years. Hence, the current status of these systems is that they are obsolete. At this stage, no refurbishments nor replacements have been done, and in general, these systems have low failure rates.

For the life extension analysis, it is assumed that the automation control system is replaced. Therefore, the condition is restored back to good, but forecasting the effects during the life extension period, it is expected that both software and hardware will be in an average condition. For software specifically, some major updates are required, but major availability in support and human competence are predicted. The automation control systems, alarm and monitoring and power management have higher integration complexity than the remaining.

The hardware components are also set to reach an average condition during the life extension period, and it is believed that support availability will be moderate, as some pieces can be broken and hard to find. Therefore, keeping spare parts of the critical ones is also suggested. No hardware is believed to be obsolete during life extension period. Compliance is achieved with none to low efforts for both hardware and software of automation systems.

ID	System	Overall System Condition	Refurbishments	Degree of Refurbishments	Replacements	Degree of Replacements	Failure and Incident	Maintenance
	Engines, Engine Room and Automation							
1	Automation System, K-Chief	Obsolete	No		No		Low	Maintained according to Software
1.1	Alarm and Monitoring System	Obsolete	No		No		Low	Maintained according to Software
1.2	Auxiliary Control System	Obsolete	No		No		Low	Maintained according to Software
1.3	Power Management System	Obsolete	No		No		Low	Maintained according to Software
1.4	Propulsion Control	Obsolete	No		No		Low	Maintained according to Software
1.5	Ballast System	Obsolete	No		No		Low	Maintained according to Software
1.6	Cargo Monitoring and Control	Obsolete	No		No		Low	Maintained according to Software
1.7	HVAC	Obsolete	No		No		Low	Maintained according to Software

ID	System	Condition Status	Failure Rates Software	Process/Data Analysis and Transfer Capability	Software Updates	Software Company	Support Availability Software	Human Competence	Compliance with Rules and Regulations Software	Complexity of Integration
	Engines, Engine Room and Automation									
1	Automation System, K-Chief	Average	Low	Moderate	Major	Major - Open	High	Available	Compliant - None to Low Efforts	
1.1	Alarm and Monitoring System	Average	Low	Moderate	Major	Major - Open	High	Available	Compliant - None to Low Efforts	High
1.2	Auxiliary Control System	Average	Low	Moderate	Major	Major - Open	High	Available	Compliant - None to Low Efforts	Moderate
1.3	Power Management System	Average	Low	Moderate	Major	Major - Open	High	Available	Compliant - None to Low Efforts	High
1.4	Propulsion Control	Average	Low	Moderate	Major	Major - Open	High	Available	Compliant - None to Low Efforts	Moderate
1.5	Ballast System	Average	Low	Moderate	Major	Major - Open	High	Available	Compliant - None to Low Efforts	Moderate
1.6	Cargo Monitoring and Control	Average	Low	Moderate	Major	Major - Open	High	Available	Compliant - None to Low Efforts	Moderate
1.7	HVAC	Average	Low	Moderate	Major	Major - Open	High	Available	Compliant - None to Low Efforts	Moderate

ID	System	Condition Status Hardware	Support Availability Hardware	Spare Parts	Compliance with Rules and Regulations Hardware	Obsoleteness	Failure Rates Hardware
	Engines, Engine Room and Automation						
1	Automation System, K-Chief	Average	Moderate	Yes	Compliant - None to Low Efforts	Not Obsolete	Low
1.1	Alarm and Monitoring System	Average	Moderate	Yes	Compliant - None to Low Efforts	Not Obsolete	Low
1.2	Auxiliary Control System	Average	Moderate	Yes	Compliant - None to Low Efforts	Not Obsolete	Low
1.3	Power Management System	Average	Moderate	Yes	Compliant - None to Low Efforts	Not Obsolete	Low
1.4	Propulsion Control	Average	Moderate	Yes	Compliant - None to Low Efforts	Not Obsolete	Low
1.5	Ballast System	Average	Moderate	Yes	Compliant - None to Low Efforts	Not Obsolete	Low
1.6	Cargo Monitoring and Control	Average	Moderate	Yes	Compliant - None to Low Efforts	Not Obsolete	Low
1.7	HVAC	Average	Moderate	Yes	Compliant - None to Low Efforts	Not Obsolete	Low

Figure 5.21: Automation Systems - Condition.

The full results of the assessment to the remaining systems can be found in Appendix C.7 - Electronic Systems. The safety management system would not be replaced after 15 years, but it does not mean that it is in a bad condition. As this thesis assumes the unit is well maintained, it is established that these systems would be requiring updates. Also, during the operating life of the unit, some moderate refurbishments would have been made into them. For the life extension assessment, the software would be in average condition. Support availability would range from low to high, depending upon the system being considered. Once again, compliance is achieved with low efforts for both hardware and software. The hardware is also predicted to be in average condition and some spare parts would be available.

After 15 years of operation, the full power system will also require upgrades. However, it does not mean that the system is not working or in bad condition. It is also not usual to replace it before life extension, as they are specific for the machinery systems already onboard the unit. These systems should have low failure rates, and refurbishments are defined as performed during operation as they have been well maintained. For the life extension period, both hardware and software will be obsolete and possibly none or low support will be available.

There is a possibility of hardware pieces being available, because components of other manufactures could be found or even some pieces stored by other companies. The human competence can be limited, as some operators will already be retired. Achieving compliance could also be very hard or even impossible, compelling high efforts to prove the system is safe and capable of operating for longer.

For navigation systems and telecommunication the outcomes were very similar. After 15 years of operation they would all be requiring updates, and moderate levels of refurbishments should already have been performed during the unit's operational life. The navigation systems are defined to have lower data transfer capability than the telecommunication ones, hence also lower integration complexity with other electronic systems. Support availability is predicted to be low for both hardware and software of these systems, and human competence will also be limited during the life extension period. To achieve compliance, high efforts are needed for both.

Risk Analysis and Risk Mitigation

Once again, all the information regarding the system condition and life extension assessment is clustered at one place to perform the risk analysis, which are presented in Table 5.14. Only the main systems are analysed, as the subsystem analysis is very similar to them.

The two higher risked systems are the automation system and electrical power systems. The automation was assigned a high likelihood as it has already reached its design life, while for the electrical power system it is already considered obsolete. The remaining have lower likelihoods, but catastrophic consequences. The worst case scenario of an electronic system not working is it affecting the FPSO production. It can be seen that the consequences forecasted range from the unit not being able to communicate externally, creating grounds for an accident, to different areas of asset not being able to communicate.

To mitigate the possible outcomes of the automation control systems, the solution is to replace it to the extend possible. For the rest of the systems, it is necessary to overhaul them completely, and then perform refurbishments and upgrades, so that these systems can be kept operating well.

Storing some critical components for future replacements and refurbishments from key components is also suggested. With these approach, the likelihoods of failures from the electronic systems are mitigated - the results can be found on Figure 5.23.

REF	System/Subsystem/Element	Life Extension Assessment Outcome
Engines, Engine Room and Automation		
1	Automation System, K-Chief	Needs to be completely replaced
2	Safety Management and Control System - K-Safe SMCS	Refurbishments and upgrades to be performed
4	Electrical Power Systems	Refurbishments and upgrades to be performed
5	Engine Monitoring System	Refurbishments and upgrades to be performed
Bridge		
5	Navigation System	Refurbishments and upgrades to be performed
Telecommunication System		
6	External Communication	Refurbishments and upgrades to be performed
7	Internal Communication	Refurbishments and upgrades to be performed

Table 5.14: Electronic Systems - Life Extension Assessment.

System		Functionality Description		Failure Description			Failure Effects			Risk		
REF	System/Subsystem/Element	Function	Life Extension Assessment Outcome	Failure Cause or Mechanism	Failure Mode	Detection of Failure	Local Effects	Global Effect	Consequences	L	S	R
	Engines, Engine Room and											
1	Automation System, K-Chief	Electronic systems that control the FPSO and its processes	Needs to be completely replaced before entering life extension period	Software outdated or Hardware Deteriorated by time	Software Failure or Hardware Damaged	Inspections in Hardwares and Updating Softwares when possible	The specifc electronic system stops working	All the Automation Systems Stop Working	Automation Lost in the entire FPSO	4	5	20
2	Safety Management and Control System - K-Safe SMCS	Electronic systems that control the FPSO and its processes	Refurbishments and upgrades to be performed	Software outdated or Hardware Deteriorated by time	Software Failure or Hardware Damaged	Inspections in Hardwares and Updating Softwares when possible	The specifc electronic system stops working	The safety management/ control system system stop working	FPSO control systems not working, hence no control of the process and functions. No safety management of the unit	2	5	10
3	Electrical Power Systems	Electronic systems that control the FPSO and its processes	It will be completely obsolete, but should be maintained normally, as full replacement is not possible	Software outdated or Hardware Deteriorated by time	Software Failure or Hardware Damaged	Inspections in Hardwares and Updating Softwares when possible	The specifc electronic system stops working	No Electrical Power supplied to the unit	Operation shut down due to lack of power	4	5	20
4	Engine Monitoring System	Electronic systems that control the FPSO and its processes	Refurbishments and upgrades to be performed	Software outdated or Hardware Deteriorated by time	Software Failure or Hardware Damaged	Inspections in Hardwares and Updating Softwares when possible	The specifc electronic system stops working	No Engine Monitoring	Possible accident scenarion with overload of engine in process systems	2	4	8
	Brigde											
5	Navigation System	Electronic systems that assist on FPSO "Navigation"	Refurbishments and upgrades to be performed	Software outdated or Hardware Deteriorated by time	Software Failure or Hardware Damaged	Inspections in Hardwares and Updating Softwares when possible	The specifc electronic system stops working	FPSO not transmitting navigation information to the other	Shuttle tanker or OSV can collide with FPSO	1	5	5
	Telecommunication											
6	External Communication	Electronic Systems to Communicate with External Sources	Refurbishments and upgrades to be performed	Software outdated or Hardware Deteriorated by time	Software Failure or Hardware Damaged	Inspections in Hardwares and Updating Softwares when possible	The specifc electronic system stops working	External Communication Lost	Shuttle tanker or OSV can collide with FPSO. Unit cannot communicate with external members.	2	5	10
7	Internal Communication	Electronic Systems to Communicate with Internal Sources	Refurbishments and upgrades to be performed	Software outdated or Hardware Deteriorated by time	Software Failure or Hardware Damaged	Inspections in Hardwares and Updating Softwares when possible	The specifc electronic system stops working	Internal Communication Lost	Problems while performing day to operation of the unit, as the different areas cannot communicate.	2	5	10

Figure 5.22: Risk Analysis - Electronic Systems.

System		Functionality Description	Risk			Risk Mitigation				
REF	System/Subsystem/Element	Life Extension Assessment Outcome	L	S	R	Mitigation Action	LM	SM	MR	Dif
	Engines, Engine Room and Automation									
1	Automation System, K-Chief	Needs to be completely replaced before entering life extension period	4	5	20	Substitute the automation system completely.	1	5	5	0.75
2	Safety Management and Control System - K-Safe SMCS	Refurbishments and upgrades to be performed	2	5	10	Perform the necessary refubishments and replacements, and keep the system in a good maintenance program	1	5	5	0.5
3	Electrical Power Systems	It will be completely obsolete, but should be maintained normally, as full replacement is not possible	4	5	20	Store spare parts for the critical components, keep a good maitnenance programs, and refurbish and replace as necessary	2	5	10	0.5
	Telecommunication System									
6	External Communication	Refurbishments and upgrades to be performed	2	5	10	Perform the necessary refubishments and replacements, and keep the system in a good maintenance program	1	5	5	0.5
7	Internal Communication	Refurbishments and upgrades to be performed	2	5	10	Perform the necessary refubishments and replacements, and keep the system in a good maintenance program	1	5	5	0.5

Figure 5.23: Risk Mitigation's - Electronic Systems.

5.3 Marine Systems - Life Extension Work Packs

To assist upon the decision making process, it was decided to create work packs that group similar works and also present a cost estimation - only the systems studied before are included in the work packs. Butler (2012) is used as reference, once the author provides guidelines on how to estimate ship repair in man-hours.

For steel and pipe works, the author defines that it includes both labor and material. Therefore, relating the dimensions with density it was possible to find a weight. The typical rate of a ship yard was not possible to find, but different sources present values of salaries in the shipbuilding industry. Selecting wages presented by Shuker (2018) as a starting point, the average salary in a Chinese shipyard is set to 1245 USD/month. Considering a work journey of 40 hours per week, this gives a value of approximately 8 USD/hour.

In order to define a yard man-hour rate, it was decided to use a profit margin of 25 %, hence a rate of 10 USD/man-hour is selected for the analysis. Again, this is a rough estimation but considered enough for performing the cost estimations in this assessment. The steel price, whenever needed was set to be 435 USD/tonnes (SteelBenchmarker, 2020).

The first work pack, WP1 - Steel Renewal, gathers all the structures and elements that require fabrication work. The life extension methodology assessed plates and stiffeners, but only considering their thickness values. The rates proposed by Butler (2012) calculate man-hours per tonnes, hence it was necessary to define the dimensions of each plate and stiffeners that required steel works.

Another result of the corrosion model considering only the thickness is that it predicts a constant scenario. One cannot assume that all the elements with same thickness will be affected at the same pace, therefore a coefficient to define what is the percentage of those plates that actually require steel work is used. In a real life scenario, these coefficients can be optimized by inspections. The total steel weight renewal was calculated to be almost 20.000 tonnes and a cost of 24 MUSD was found.

WP2 - Hull Painting describes the painting work to be performed in the external areas of the hull. The submerged area is decided not to be painted, but anodes shall be replaced there (treated in another WP). Thus, to determine the external area of the hull that shall received painting treatment the required areas were exported from the 3D model - same process was done for accommodation region and process deck area. Due to lack of information, a rate of 10 USD/m2 was selected. This assessment considers that almost 30.000 m2 required painting, at a total cost of about USD 300.000. However, this value represents just the core paint work itself, and does not include the prices in case this has to be done in the yard or offshore.

Anodes replacement are presented in WP 3. In order to predict the total man-hours required, the total weight of anodes was calculated as function of underwater hull area. A replacement frequency of 5 years is assumed, and a general weight of 10 kg requiring 1.5 man-hours per kg was selected. The rate of 10 USD/man-hours was used again and a value of approximately USD 30.000 is calculated for WP3.

Firefighting assessment showed that some valves were in bad condition and required repair. With the objective to cost the work pack, it is defined that 20 valves with 150 mm bore require the overhaul, and using the same rate as before, a value of USD 2.300 is found for this work pack.

The hypothesis used during the life extension assessment assumed that, as the pipes reached the criteria they were substituted. Hence, there is no need to replace any of the pipes analysed now - only when they reach the criteria during the life extension period. No work packs for pipes are created.

The offloading hose replacement is covered by WP5. A value of USD 200.000 was selected for the work. The main engines overhauls are covered by WP6, and the calculations are made based on the decisions of what systems shall be overhauled or not in Section 4.3.1. Most dimensions and quantities for the calculations were found in Wartsila 46DF product guide, but whenever necessary assumptions were made to be able to cost the work pack. To overhaul all the defined components before entering the life extension period, over 17.000 man-hours are required, at a total cost of USD 178.000 - for the 6 main engines.

Painting of all ballast tanks and the required areas in cargo tanks are covered by WP 8, and it assumes the same methodology as WP 2. The cargo tanks areas to be painted are calculated considering the hypothesis that only 2m above baseline and 2m below deck level are required to be painted, and a total cost of over USD 500.000 was estimated.

All the work packs created are presented in Table 5.15. It is important to notice that these work packs do not contain all the work required for the fictional FPSO. For instance the scope of work for control and telecommunication system is not included, as it was not possible to find values for it. Also, it is just an estimation and the rates are not representing the reality. The full analysis and considerations made into work packs can be found in Appendix C.8 - Life Extension Work Packs.

Workpack	Description	Location	Cost
WP 1 - Steel Renewal	Steel Renewal of Plates and Stiffeners	Yard Stay	$ 23,858,994.38
WP 2 - Hull Painting	Painting of External Hull Areas	Yard Stay	$ 292,486.09
WP 3 - Anodes Replacement	Replacement of Anodes in Underwater Area of the Hull	Yard Stay	$ 29,503.67
WP 4 - Firefighting Valves Replacements	Replacement of Valves that are in bad condition from Firefighting Systems	Yard Stay	$ 2,300.00
WP 5 - Offloading Hose Replacement	Replacement of Offloading Hose	Yard Stay	$ 100,000.00
WP 6 - Overhaul Main Engine	Overhaul of Main Engines	Yard Stay	$ 177,773.87
WP 7 - Overhaul of Pumps	Overhaul of firefighting and cargo pumps	Yard Stay	$ 5,856.00
WP 8 - Tank Painting	Painting of Internal Areas in Ballast Tanks and required areas of Cargo Tanks	Yard Stay	$ 555,560.00
Total Cost			**$ 25,022,474.01**

Table 5.15: Life Extension - Work Packs Cost.

5.4 FPSO Life Extension Decision Making and Discussion of the Results

The decision of whether the unit is suitable for life extension or not is based on a economical framework. For this analysis, it is assumed that the cost for the company are CAPEX and OPEX. CAPEX is the initial investment cost, therefore all the money that has to be invested in the unit to make it suitable for life extension, while OPEX is related to the operational cost to keep the unit running. The only source of income analysed here is the rate the company receives with the asset, hence the charter rate for the FPSO.

OPEX costs tend to increase as the unit gets older, because more systems will require maintenance and even replacement, however as a simplification for this master thesis it is kept constant. Also, the shipowner/operator will probably require financing to obtain the necessary CAPEX value, and that should be considered in the analysis.

The information provided by Kurniawati et al. (2016) in the article “Long-term FSO/FPSO Charter Rate Estimation” is used as reference to perform the feasibility analysis of the life extension project. The author provided OPEX data for a 261m long FSO. A simple linear analysis using the units lengths was performed to define the rates for the fictional FPSO, rounding up the values for a better visualization later on - the results are presented in Table 5.16. The FPSO has an OPEX rate of USD 1.119.200,00 per year.

OPEX ESTIMATION	Kurniawati et al. (2016) USD/year	Thesis FPSO Estimated USD/year	Selected USD/Year
Crew	$ 201,196.00	$ 241,049.77	$ 242,000.00
Maintenance and Repairs	$ 50,000.00	$ 59,904.21	$ 60,000.00
Administration and Genral Charges	$ 25,000.00	$ 29,952.11	$ 30,000.00
Lub Oil	$ 6,000.00	$ 7,188.51	$ 7,200.00
Insurace	$ 600,000.00	$ 718,850.57	$ 720,000.00
Provisions and Stores	$ 50,000.00	$ 59,904.21	$ 60,000.00
Total Operating Cost (USD/Year)	$ 932,196.00	$ 1,116,849.38	$ 1,119,200.00

Table 5.16: FPSO OPEX Estimation.

The CAPEX value of a life extension or redeployment project varies depending upon the condition of the unit and location of field for extended operating time. Evans (2017) presented cost impact values for EnQuest Producer of over 200 MUSD. Offshore-Mag (2017) states that Petrojarl I costed 183 MUSD to be redeployed for Brazil, and that Petrojarl Varg is expected to have upgrade costs ranging from MUSD 100 - MUSD 400.

The cost for the work packs defined in Section 5.3 was estimated to be about MUSD 25. As explained before, it does not consider all the work required for the marine systems, even the less is a full approximation of the total cost considering yard work. Therefore, it was decided to define some factors and some hypothesis were made that could return a CAPEX value within a range of MUSD 100 - MUSD 200. The defined work packs are set to represent 20 % of the total work needed, which represents 80 % of the CAPEX for the FPSO. Thus, a CAPEX value of MUSD 157 is found for this assessment.

The shipowner/ship operator has a budget of 30 % and needs to finance the rest, hence approximately MUSD 110. The same interest rates as presented by Kurniawati et al. (2016) is selected, 10 %/year, and the financing period is the same as life extension (10 years), Using a simple financing technique (assuming constant annual payments and interest rates, and not considering depreciation or inflation), the company has to pay USD 17,816,279.31 per year during the extended operational life. The value invested by the company is diluted over the life extension period, thus considered as a annual expenditure.

Another parameter necessary to assist in the decision making is the value of selling the vessel for scrap. A rate of 375 USD/LDT (LDT - Light Displacement Tonnes) is used based on rates from Roussanoglou (2019). Using the regression analysis presented in Appendix B - FPSO Description, the FPSO has an estimated LWT of 40.190 ton, hence a total value of around MUSD 15 (USD 15.071.250,00) can be expected if it sold for scrap.

The FPSO operating days per year is assumed to be 360 days, and the profit margin is defined to be variant over the life extension period. As the end of the period is reaching, the profit margin is lowered, and the selected values are presented in Figure 5.24.The profit margins are used to calculate the minimum required charter rates for the project to be over the annual expenditures, and those are defined as unique for each extended operational year.

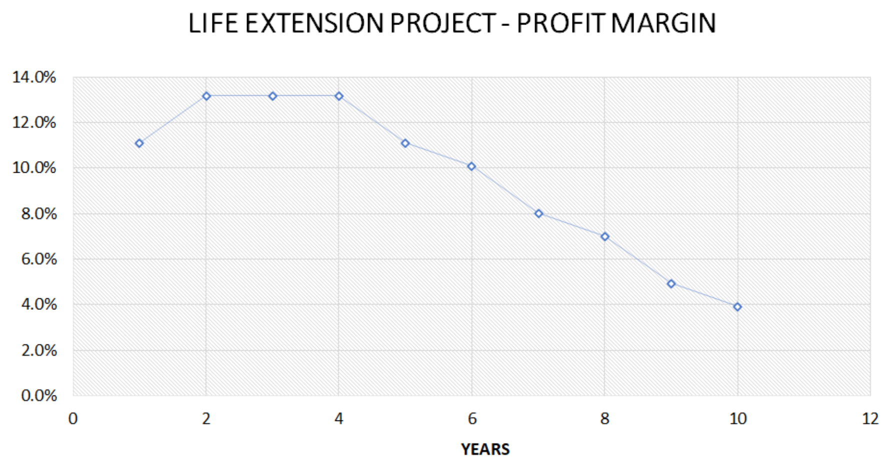


Figure 5.24: Profit Margin for Life Extension Period.

For this master thesis, it is set that the life extension project is only suitable if the shipowner gets back 50% more than selling the unit. Hence, the total revenue required over the 10 years period is known and the model is recalculated to find the required charter rate to achieve this goal. Table 5.17 presents the values for charter and Figure 5.25 gives an overview of the economical framework results.

YEAR	CHARTER RATE	REVENUE
1	$ 72.923,61	$ 2.625.305,54
2	$ 74.274,04	$ 3.111.462,92
3	$ 74.274,04	$ 3.111.462,92
4	$ 74.274,04	$ 3.111.462,92
5	$ 72.923,61	$ 2.625.305,54
6	$ 72.248,39	$ 2.382.226,85
7	$ 70.897,95	$ 1.896.069,46
8	$ 70.222,73	$ 1.652.990,77
9	$ 68.872,30	$ 1.166.833,39
10	$ 68.197,08	$ 923.754,69
	TOTAL	$ 22.606.875,00

Table 5.17: FPSO Charter Rates Based on Required Revenues.

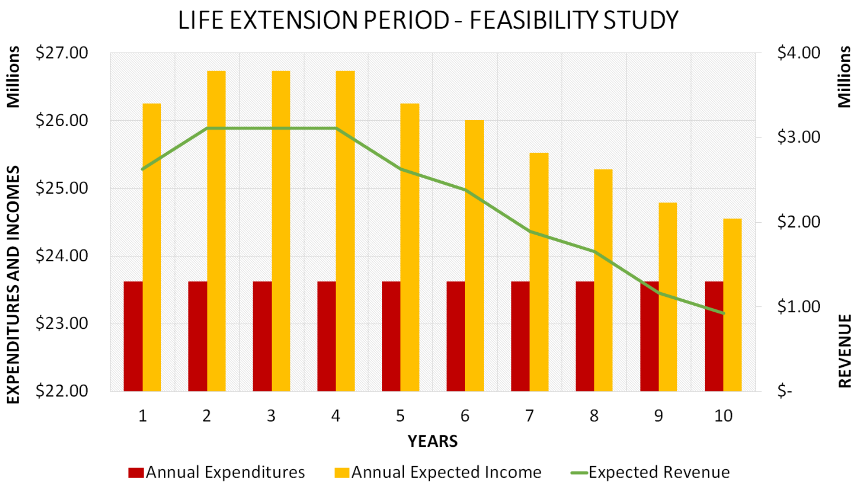


Figure 5.25: Forecasted Economical Framework for Life Extension Period.

To check whether these rates are achievable, an analysis considering the oil price and production forecast is made. As in May 2020, the world is suffering from the corona crisis that has heavily hitten the oil industry, with oil prices going even negative. Obviously, this is not something that shall last forever, and as presented in the introduction before, the oil price changes in a cyclic behaviour and hence, sometime the oil price will recover. At the time of this assessment (08/05/2020), the brent crude oil price is just around USD 30.00 per barrel - in position to June 2019, where the price was around USD 70.00.

In the offloading analysis made before, it was detailed that the FPSO had been responsible for 25% of the field production for over the last 15 years of operation. For the life extension period, it shall be responsible for the same amount - 25% of the production. Hence, it is predicted that the FPSO will offload 521.840.500 barrels.

For this assessment, the thinking is done considering the company chartering the FPSO, and not FPSO owner anymore. Hence, keeping the assumption that they would charter the asset 360 days per year, the amount of daily production can be calculated and compared to the FPSO processing capacity to check whether it would still be a fit - the results are presented on Figure 5.26.

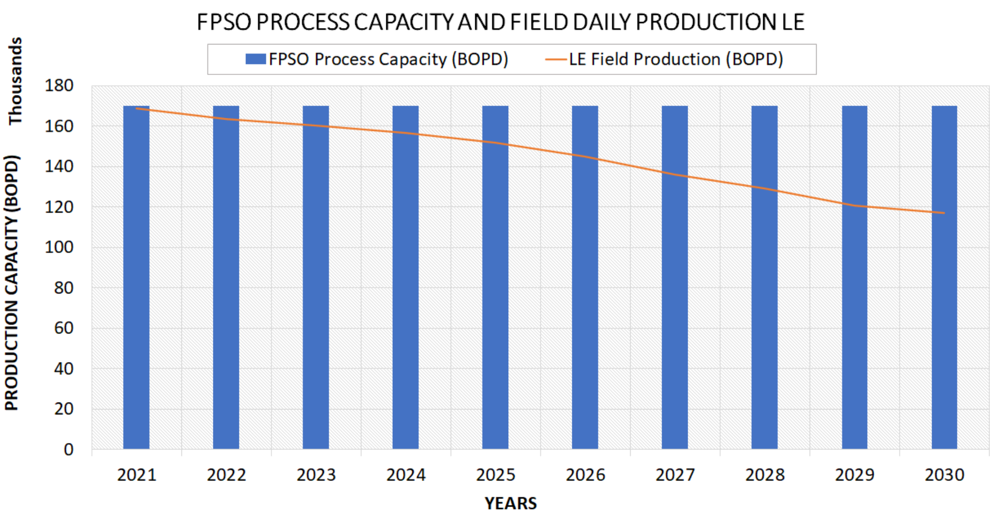


Figure 5.26: Field and FPSO Production Capacity during Life Extension Period.

From the total sales price, the oil companies should be able to pay all the required rates with exploration, transportation, FPSO charter, salaries, provisions and so on, while making a descent profit. Therefore, a fraction of total sales is destined to rent the FPSO and to pay all the necessary taxes related to it. Assuming that only 1% of total forecasted sales value is destined for chartering expenses, that the predicted production will actually occur, and considering the minimum rate calculated for the FPSO owner to have the defined profit during life extension period, one can predict what is the minimum average oil price rate required for each operational year.

For this project to be viable with all the hypothesis and assumptions made, the oil price will need to be at least USD 43.17 at the start of life extension period, reaching up to USD 58.19 in the last year. Based on the oil price history, these values are not outside typical variation rates, but the current world situation leaves an uncertain scenario of whether the prices will pick up again soon. Hence, with the current brent price of around USD 30.00, the life extension project is not feasible.

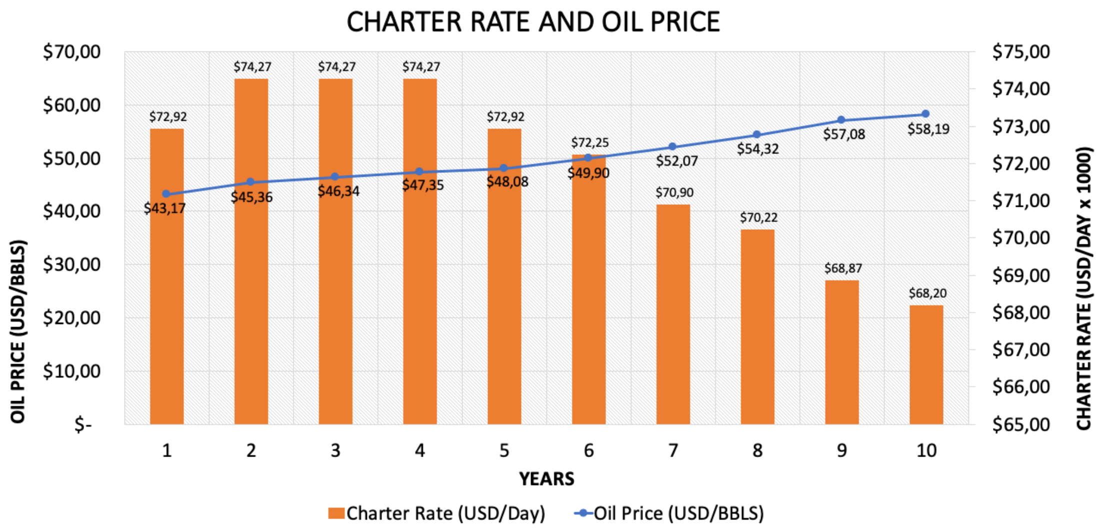


Figure 5.27: Minimum Oil Price for Project Viability.

5.5 Analysis of the Results

During the development of the methodology and testing out the models into a FPSO, many challenges were faced. Deciding upon main dimensions and performing naval architecture calculations was somewhat a straight forward process with wide available literature and guidelines. However, the FPSO requires more work than a regular merchant vessel.

It is not only a ship, but also a factory for processing oil. Hence, different disciplines and knowledge is involved while designing it. The marine systems selected for the study also had different degrees of difficulties for their definitions. Some have a wide variety of information online and in books, such as the vessel's midship section and diesel engines, while others require a full assessment on their own - like the piping system.

As a result, some of the studied systems are well defined and accordingly to real life scenarios, while others can be with over dimension's and not a true representation of that systems. Also, when doing a life extension methodology, the current condition of the unit is considered and not the design life. Initially, this was also the objective of the study - using current values that could be available on inspection reports - notwithstanding, as the information started to be gathered for testing, it was seen that it was not possible to define the values as current condition because they were more related to fabrication characteristics. To solve this problem, the results were used as reference and replacement criterion were selected - if the results reached the criteria within the first operation time frame (15 years), they were substituted. Therefore, their initial life is started again and the current value could be found.

Before testing out the proposed models, many assumptions were necessary. Defining the oil field in a tropical area gives information into corrosion effects, which are expected to be high. However, selecting accurate corrosion rates was very complicated, once it depends in many effects such as temperature, fluid type and velocity. Coating life also influences how corrosion happens, hence it was included into the analysis based on coating area coverage found in DNV RBI guidelines. Although the guidelines are for topside rotating equipment, the same process was kept for all the steel components - structural steel plates, stiffeners, and pipes.

The rotating equipment also required an operational profile. In reality, the same group of equipment does not run at similar pace - some runs for longer while others are used less. Accordingly, an operational profile was defined both for offloading frequency and power generation. This resulted in different overhauls time frames for the systems, which are closer to the real condition of a vessel operating offshore.

The risk analysis performed was solely qualitative, and keeping the mindset for worst case scenario always. This was necessary to limit the amount of hazards found, because if each system was to be evaluated in a complete detail, the assessment would be huge. Therefore, keeping in mind the worst that could happen during life extension period if the system's condition was kept resulted in a conservative assessment.

With the scope of work for life extension delineated, work packs were created. This was done based on guidelines available in the literature, hence the total man-hours should be a good approximation of reality. However, the yard rates used were based on information from wages in Chinese shipyards, and may not represent the actual value that is charged.

The economical analysis also required different sorts of hypothesis and assumptions, including assuming profit rates, constant charter rates, scrap selling values and so on. It included assessments made for the two main stakeholder in FPSO leasing: the company that owns and operates the vessel, and the oil company that will use it. The project feasibility was measure as an oil price value: the minimum value for the project to be profitable for both companies during the life extension period was found. This is an important indicator for decision-makers to conclude whether the project is feasible or not.

Eventhough many assumptions and hypothesis were required during the case study, and with the possibility of over dimensioned systems, the models worked and the methodology proved to be efficient. The final result - the oil price to have a profitable project - ranges from USD 43.17 to USD 58.19 which is a realist price based on past rates.

Chapter 6

Concluding Remarks and Suggestions for Further Work

This chapter presents the concluding remarks considering the thesis development. The importance of life extension projects is summarized and the outcomes of the proposed methodology are also presented. The challenges faced and areas that need improvements are also discussed, and the section finishes by justifying why the results were considered acceptable. Lastly, different suggestions for future work are made - including areas that could be improved and new case studies.

6.1 Concluding Remarks

The oil and gas industry is an important stakeholder for different sectors of the economy. In one way or another, everyone is affected by it - it can be the fuel used to power our vehicles, the gas people use to cook, or somebody we know that works within its supply chain. Oil price is the main factor shaping the industry, with ups and downs happening in a cyclic behaviour.

As in 2020, the world is experiencing a terrible scenario, with very low oil price. This affects directly oil exploration projects - lower prices do not make it attractive to build new offshore structures nor explore new oil fields. From previous years, when the oil prices start to recover, a trend in the industry can be observed - utilizing existing facilities at the same oil field or redeploying it to another location.

The main objective of the master thesis was to investigate the possibility of creating a methodology to assess life extension of FPSO units, and it can be concluded that it is possible to do so. Considering the decommissioning phase of the unit's life cycle, it was seen that an important factors to be addressed are the asset condition and required work scope to achieve compliance to operate for longer periods.

Depending upon the vessel's condition, the amount of work required to achieve enough compliance that allows for longer operation is not viable at all - it can even be higher than building a new ship. However, some FPSOs can experience at least a redeployment or life extension project during its life cycle.

Therefore, it is necessary that companies can keep up with the asset's condition in order to maintain time in production and safety high, and also performing faster and accurate life extension and redeployment studies. The way the thesis organizes the information is required is by utilizing concepts that are already used and organize them into different models. Qualitative condition assessment and remaining useful life are concepts widely studied and used in the process industry. The qualitative tool that gathers the necessary information about the current asset condition is powerful for life extension work - all the information needed is grouped into one place. Hence, the access is easy and fast, and should be accurate as long as it is updated. Nevertheless, all the models created are tested out and information available is organized for marine systems and subsystems.

Predicting the remaining life gives important information to decision makers, as they can forecast what would the actual condition of systems be during the extended operational time. Therefore, they can decide more precisely what is the extend of work required and what systems will need full replacement. These values also allow for a risk analysis - the likelihoods and consequences can be optimized based on life and condition assessments. Most of the risks found for life extension are in relation to system failure, and they can be mitigated by performing the necessary refurbishments and replacements before entering the new operational time.

As most projects, the final decision parameter when doing the life extension project is money. To assess it, the scope of work is transformed into work packs that are later costed. Depending on the investment prices and the predicted revenues, the project is considered feasible or not. To validate the methodology and provide input to the decision-making, a economical feasibility analysis was performed considering two stakeholder of the offshore industry: shipowner/operator and oil company. For shipowner/operator, the decision-making can be done considering the minimum required charter rate to achieve a set of goals, while for the oil company the analysis is performed by estimating what would be the revenue with oil barrels sale. The final result is a minimum oil price required for the project to be profitable for both stake-holders.

The master thesis was developed into 3 main areas - research, methodology development and case study. Although they were presented in a linear structure, all the process iterate with each other. While developing the models to be tested, it was necessary to run into literature to review the concepts and decide upon hypothesis.

Selecting a FPSO for the study was very challenging. Ships have been around for a long time, but FPSOs are somewhat new - the first one came around late 1970s. In shape, they resemble a big oil tanker, but they also have a factory on their main deck.

Different studies have been done about FPSOs and processes linked to them. Even so, most of the assessment are made for specific systems instead of the entire unit. Defining a size, shape and basic naval architecture parameters was easy, but describing fully all the systems onboard the unit was very challenging. Not withstand, the quantity of systems to make a floating production work properly is huge, thus a screening factor was needed to select what systems would be studied. The focus should be the marine systems, as they are closer to the master program Ship Design.

The structural midship section, the firefighting system, offloading system, power generation system and electronic systems were the selected ones for the thesis assessment. However, for some subsystems the definitions were based on best guesses. The piping system dimensions, for instance, were selected from available suppliers online, but could be with wrong dimensions.

A life extension assessment is done after the unit has operated for longer, hence should use current data about the unit. When predicting the corrosion effects over steel plates, the correct manner is using thickness from inspection reports. However, the data used in the thesis is from design and fabrication values, therefore the models were adapted and criterion were used so that the assessment could actually predict remaining useful life.

The corrosion rates also turned out to be a real challenge. It is not possible to have only one steel corrosion rate for one type of fluid, as different factors affect it. Hence, the values used on the thesis are merely a estimate and should be used cautiously. Ideally, the models should have been tested with thickness values from inspection reports and corrosion rates based on experiments for that specific location.

The cost analysis is performed in a simplified manner, pricing work packs and by a economical analysis considering CAPEX and OPEX. Although the final outcome of the analysis were oil prices within realistic rates, different judgments were made for profit rates and charter rates that could be optimized to represent a more realistic business case.

Looking back into past oil prices, the range is not out of a normal and expected scope. Consequently, it is acceptable to say that the methodology has proved to work and could be used in a real case scenario. All the work that was performed individually, when brought together delivered acceptable results. Thus, proportionally the values selected are good and the hypothesis are balanced, but individually they might need to be optimized.

The models developed are easy maintainable, hence if data is updated, studies considering the decommissioning phase can be done in a fast and efficient manner. Also, the models can be used to forecast maintenance work in some key areas, thus proposing optimized maintenance schemes. They way the models were created also allow for the development of dashboards for each system and the entire FPSO - this is a powerful tool to easily visualize the condition and allow for faster and efficient decision making.

6.2 Suggestions for Further Work

This master thesis addressed different topics, and hence creates the possibility of various future development. Addressing the case study, it was tested out with a mock up FPSO - with systems defined from various sources and different hypothesis and assumptions were made. As a suggestion, the methodology could be applied in a real FPSO, thus using real data. Another hypothesis that could be changed is the maintenance condition - possibly utilizing something more realistic than the best case scenario where most of systems are very well maintained and replaced whenever a problem is found.

The systems studied were only some of the marine systems, therefore further work can be done including the process systems. This allows for the development of more quantitative models with different degradation mechanisms. The risk analysis was done in a qualitative way, but it is possible to also extend it for a quantitative assessment. This could include for instance probability data on failure rates, event and fault tree analysis, and Bayesian belief networks.

Optimization is also an outcome that could be performed, studying what would the minimum and maximum profit margin to be achieved for a life extension project. This methodology can also be used to address what type of system are driving most of the work in life extension and using it as a lessons learned. It can give input to companies on how to adapt their maintenance strategies focusing on extending the life of the assets.

Lastly, each of the quantitative models can be developed further into more detailed levels. For example the corrosion models can be updated and calibrated with information from risk based inspection. Experimental work on corrosion rates can also be done, as more realistic values could be used for the specific region where the FPSO is located. The models can also be developed to integrate with other engineering techniques - such as finite element analysis of the hull girder - what would provide for more accurate results from the life extension project.

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Appendices

Appendix **A**

Methodology Development

A.1 Structural Components

A.1.1 Identify and Organize Structural Components

ID No.	Member Type	Example
1	B/S-H	Bottom shell plating (segregated ballast tank)
2	A/B-H	Deck plating (segregated ballast tank)
3	A/B-V	Side shell plating above draft line (segregated ballast tank)
4	B/S-V	Side shell plating below draft line (segregated ballast tank)
5	BLGB	Bilge plating (segregated ballast tank)
6	O/B-V	Longitudinal bulkhead plating (segregated ballast tank)
7	B/B-H	Stringer plating (segregated ballast tank)
8	O/S-H	Bottom shell plating (cargo oil tank)
9	A/O-H	Deck plating (cargo oil tank)
10	A/O-V	Side shell plating above draft line (cargo oil tank)
11	O/S-V	Side shell plating below draft line (cargo oil tank)
12	BLGC	Bilge plating (cargo oil tank)
13	O/O-V	Longitudinal bulkhead plating (cargo oil tank)
14	O/O-H	Stringer plating (cargo oil tank)
15	BSLB(W)	Bottom shell longitudinals in ballast tank, web
16	BSLB(F)	Bottom shell longitudinals in ballast tank, flange
17	DLB(W)	Deck longitudinals in ballast tank, web
18	SSLB(W)	Side shell longitudinals in ballast tank, web
19	SSLB(F)	Side shell longitudinals in ballast tank, flange
20	LBLB(W)	Longitudinal bulkhead longitudinals in ballast tank, web
21	LBLB(F)	Longitudinal bulkhead longitudinals in ballast tank, flange
22	BSLC(W)	Bottom shell longitudinals in cargo oil tank, web
23	BSLC(F)	Bottom shell longitudinals in cargo oil tank, flange
24	DLC(W)	Deck longitudinals in cargo oil tank, web
25	DLC(F)	Deck longitudinals in cargo oil tank, flange
26	SSLC(W)	Side shell longitudinals in cargo oil tank, web
27	SSLC(F)	Side shell longitudinals in cargo oil tank, flange
28	LBLC(W)	Longitudinal bulkhead longitudinals in cargo oil tank, web
29	LBLC(F)	Longitudinal bulkhead longitudinals in cargo oil tank, flange
30	BGLC(W)	Bottom girder longitudinals in cargo oil tank, web
31	BGLC(F)	Bottom girder longitudinals in cargo oil tank, flange
32	DGLC(W)	Deck girder longitudinals in cargo oil tank, web
33	DGLC(F)	Deck girder longitudinals in cargo oil tank, flange
34	SSTLC(W)	Side stringer longitudinals in cargo oil tank, web

Figure A.1: Definition of Member Groups (Paik et al., 2003)

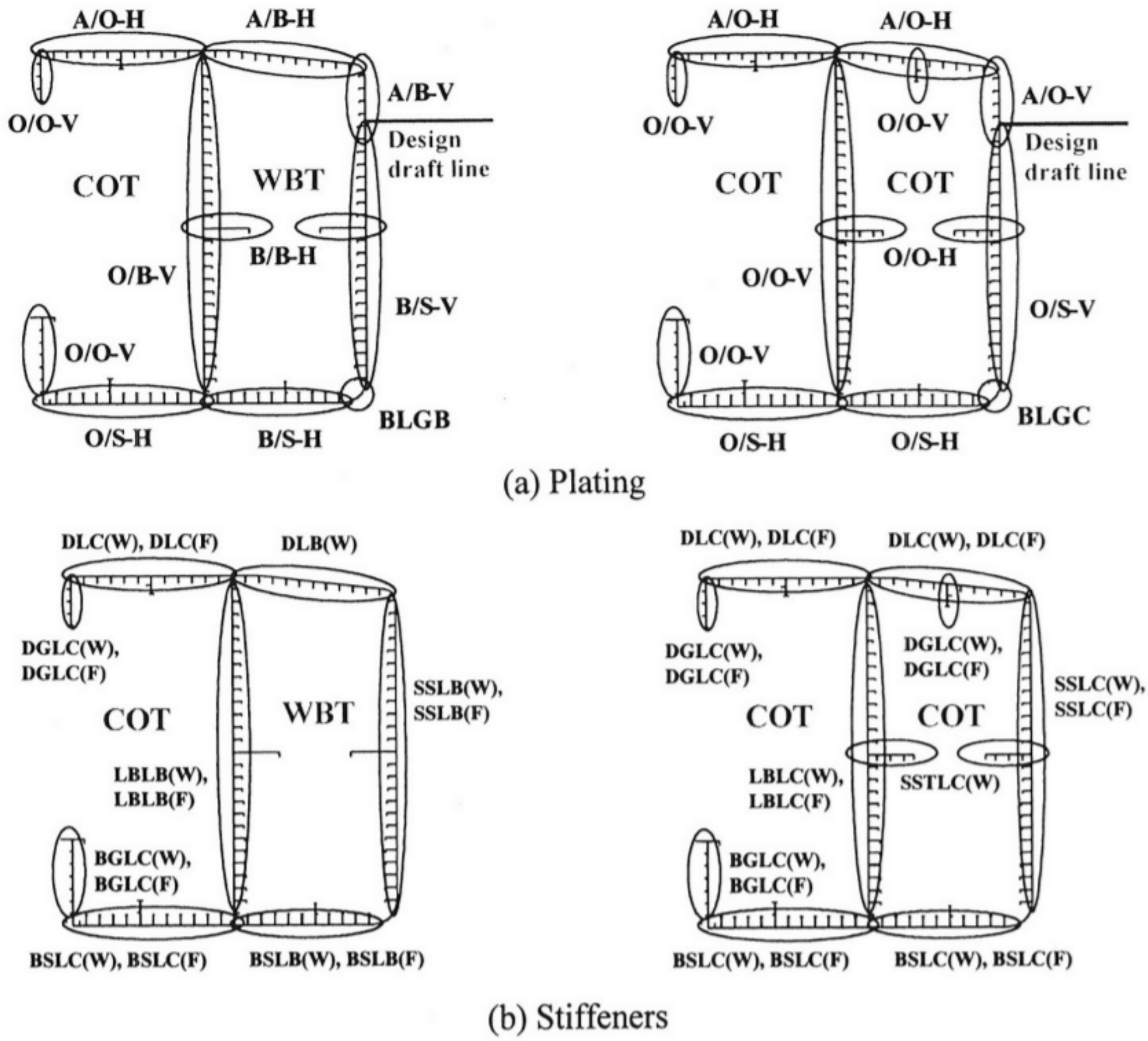


Figure A.2: Identification of Member Groups (Paik et al., 2003).

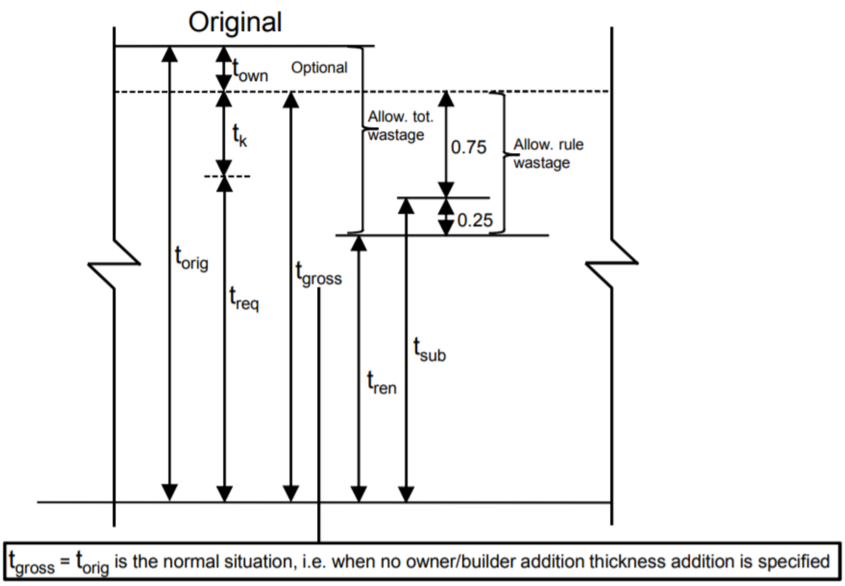


Figure A.3: Gross Thickness Definition (DNVGL, 2015)

A.1.2 Define Thickness Reduction Criteria

Allowable diminution coefficients for longitudinal strength members

Structural component	*Diminution coefficients "k"*	*Diminution coefficients "k_{sub}"*	*Buckling control*
Plating	0.80	0.85	according to [2.3.7]
Stiffeners	0.75	0.81	according to [2.3.7]
Girders and stingers	0.80	0.85	according to [2.3.7]

Figure A.4: Allowable Diminution Coefficient for Longitudinal Strength Members (DNVGL, 2015)

Diminution coefficients for transverse members

Structural component		*Diminution coefficients "k"*	*Diminution coefficients "k_{sub}"*
Transverse Bulkheads	Plate	0.75	0.81
	Stiffeners	0.75	0.81
Web-frames/Floors/ Girders and stringers *)	Plate	0.80	0.85
	Stiffeners	0.75	0.81
Cross ties web and flange	Web	0.75	0.81
	Flange		
*) Flanges on transverse members contributing to hull girder section modulus are to be considered according to Table 2-1			

Figure A.5: Allowable Diminution Coefficient for Transverse Strength Members (DNVGL, 2015)

Diminution coefficients for other structural members

Structural component		*Diminution coefficients "k"*	*Diminution coefficients "k_{sub}"*
Super structure and deckhouse	Plate	0.7	0.78
	Stiffeners		
Forecastle and poop deck	Plate	0.80	0.85
	Stiffeners	0.75	0.81
Hatch covers and hatch coamings	Plate	0.75	0.81
	Stiffeners		

Figure A.6: Allowable Diminution Coefficient for Other Structural Members (DNVGL, 2015)

Diminution coefficients for topside structure and topside interface members

Structural component	*Diminution coefficients "k"*	*Diminution coefficients "k_{sub}"*
Special areas	0.95	0.96
Primary areas	0.90	0.92
Secondary areas	0.85	0.88

Figure A.7: Allowable Diminution Coefficient for Interface Members (DNVGL, 2015)

A.1.3 Establish Corrosion Rates mm/year

ID No.	Member type	Average corrosion rate by the Paik model (mm/year)	Severe corrosion rate by the Paik model (mm/year)	Corrosion rate by TSCF (mm/year)
1	B/S-H	0.0597	0.1717	0.04–0.10
2	A/B-H	0.1084	0.2323	0.10–0.50
3	A/B-V	0.0661	0.1897	0.06–0.10
4	B/S-V	0.0622	0.1823	0.06–0.10
5	BLGB	0.0619	0.1805	–
6	O/B-V	0.1012	0.1919	0.10–0.30
7	B/B-H	0.1408	0.2586	–
8	O/S-H	0.0607	0.1777	0.04–0.10
9	A/O-H	0.0581	0.1689	0.03–0.10
10	A/O-V	0.0523	0.1529	0.03
11	O/S-V	0.0423	0.1497	0.03
12	BLGC	0.0414	0.1446	–
13	O/O-V	0.0577	0.1621	0.03
14	O/O-H	0.0405	0.1423	–
15	BSLB(W)	0.1367	0.2461	–
16	BSLB(F)	0.1127	0.2343	–
17	DLB(W)	0.2403	0.4244	0.25–1.00
18	SSLB(W)	0.1413	0.2595	0.10–0.25
19	SSLB(F)	0.0882	0.1630	–
20	LBLB(W)	0.1960	0.3840	0.20–1.20
21	LBLB(F)	0.1782	0.3455	0.20–0.60
22	BSLC(W)	0.0466	0.0888	0.03
23	BSLC(F)	0.0437	0.0837	–
24	DLC(W)	0.0716	0.1252	0.03–0.10
25	DLC(F)	0.0588	0.1060	–
26	SSLC(W)	0.0420	0.0810	0.03
27	SSLC(F)	0.0397	0.0790	–
28	LBLC(W)	0.0550	0.0942	0.03
29	LBLC(F)	0.0508	0.0921	–
30	BGLC(W)	0.0377	0.0714	–
31	BGLC(F)	0.0319	0.0578	–
32	DGLC(W)	0.0477	0.0900	–
33	DGLC(F)	0.0449	0.0862	–
34	SSTLC(W)	0.0261	0.0437	–

Figure A.8: Corrosion Rates proposed by (Paik et al., 2003).

A.2 Pipes

A.2.1 Define Minimum Wall Thickness and Corrosion Allowance

Table A2 Minimum wall thickness for steel pipes

External diameter D (mm)	*Pipes in general* 3) 4) 5) 6) 7) 8)	*Air, overflow and sounding pipes for structural tanks* 1) 2) 3) 5) 8) 9)	*Bilge, ballast and general seawater pipes* 1) 3) 4) 5) 7) 8)	*Bilge, air, overflow and sounding pipes through ballast or fuel oil tanks, ballast lines through fuel oil tanks and fuel oil lines through ballast tanks* 1) 2) 3) 4) 5) 7) 8) 9)
10.2 - 12	1.6			
13.5 - 17.2	1.8			
20	2			
21.3 - 25	2		3.2	
26.9 - 33.7	2		3.2	
38 - 44.5	2	4.5	3.6	6.3
48.3	2.3	4.5	3.6	6.3
51 - 63.5	2.3	4.5	4	6.3
70	2.6	4.5	4	6.3
76.1 - 82.5	2.6	4.5	4.5	6.3
88.9 - 108	2.9	4.5	4.5	7.1
114.3 - 127	3.2	4.5	4.5	8
133 - 139.7	3.6	4.5	4.5	8
152.4 - 168.3	4	4.5	4.5	8.8
177.8	4.5	5	5	8.8
193.7	4.5	5.4	5.4	8.8
219.1	4.5	5.9	5.9	8.8
244.5 - 273	5	6.3	6.3	8.8
298.5 - 368	5.6	6.3	6.3	8.8
406 - 457	6.3	6.3	6.3	8.8

1) For pipes efficiently protected against corrosion, the thickness may be reduced by 20% of the required wall thickness but not more than 1 mm.
2) For sounding pipes, except those for cargo tanks with cargo having a flash point less than 60°C, the minimum wall thickness is intended to apply to the part outside the tank.
3) For threaded pipes, where allowed, the minimum wall thickness shall be measured at the bottom of the thread.
4) The minimum wall thickness for bilge lines and ballast lines through deep tanks and for cargo lines is subject to special consideration.
5) For larger diameters the minimum wall thickness is subject to special consideration.
6) The wall thickness of pipes within cargo oil and ballast tanks in systems for remote control of valves shall be no less than 4 mm.
7) For inlets and sanitary discharges, see Pt.3 Ch.3 Sec.6.
8) For stainless steel pipes, the minimum wall thickness will be specially considered, but it is in general not to be less than given in Table A3.
9) For air pipes on exposed decks, see Pt.3 Ch.3 Sec.6.

Figure A.9: Minimum Wall Thickness Proposed by (Veritas, 2008)

A.2.2 Pipe Methodology Illustration

To illustrate this methodology, a set of hypothetical information is proposed assuming that historical data on corrosion is available. The inputs and criterion are presented in Table A.1.

Marine Pipe	Seawater System		
Name	Value	Unit	Observation
t_0	7,0	mm	Initial Pipe Wall Thickness at Year
t_M	5,0	mm	Measured Pipe Wall Thickness at Year
D	200,0	mm	Pipe External Diameter
Criterion			
c	3,0	mm	Corrosion Allowance
t D	3,8	mm	MAWT Design Pressure
t SV	1,5	mm	MAWT Safety Valve
t OP	2,8	mm	MAWT Operating Pressure’

Table A.1: Seawater Piping Example

Internal corrosion degradation from 2005 to 2019 is defined and named $d(t)$, and this is the total corrosion assuming that no maintenance was made during the pipe operation to increase the wall thickness.

The data is plotted and an equation is found to forecast the future degradation. As the initial pipe wall thickness is known, t_0, it is possible to calculate what is the thickness after the effects of corrosion.

If information is available about the current wall thickness of the pipe (measured wall thickness value), it is possible to adjust the analysis to use this value. That is, from the forecast made before, a value from corrosion rate in (mm/year) can be found by the following formula:

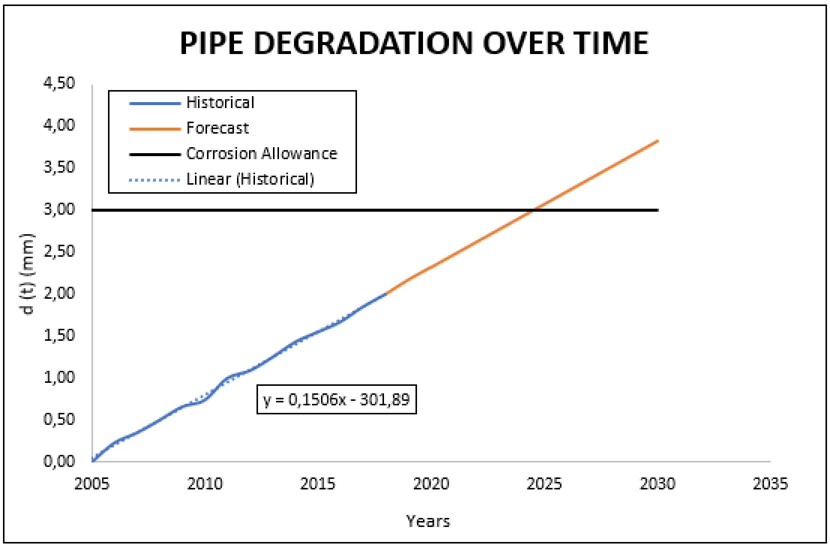
$$c'(t) = t_{i+1} - t_i \tag{A.1}$$

Where $c'(t)$ is the corrosion rate, i is the year, t_{i+1} is the estimated wall thickness at (i+1) and t_i is the wall thickness at i. Hence, from the measured pipe diameter, the wall thickness is calculated as before and presented in Equation A.2, but now the input value is the measured one and this shall be formed only for the life extension period.

$$t(t) = t_M - c'(t) \tag{A.2}$$

Figure A.10 presents the results from the assessment. The first plot, Pipe Degradation Over Time, presents the information regarding the corrosive effects. The first criterion can be seen there - the corrosion allowance. For this example, the forecasted effects overcome the maximum corrosion allowance, thus this is a factor that should be analysed later.

The second plot, Pipe Wall Thickness, presents the other three criterion with regards to minimum allowable wall thickness. The hypothetical pipe crosses the limit for the design thickness, and this should also be studied next.



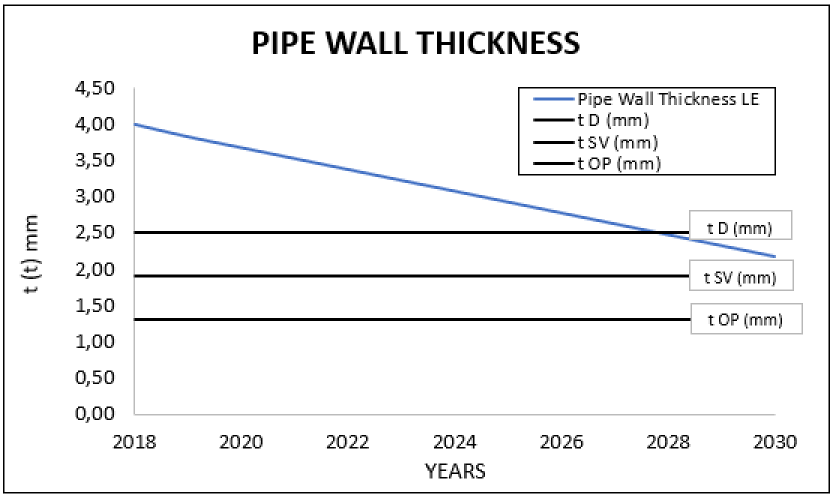


Figure A.10: Example for the Proposed LE Assessment

A.3 Power Generation System

A.3.1 Wartsila 46DF

Component	Time between inspection or overhaul (h)		
	LFO operation	HFO1 operation	HFO2 operation
Twin pump fuel injection			
- Injection nozzle			
- Injection pump element	12000	12000	12000
Cylinder head	20000	16000	12000
- Inlet valve seat			
- Inlet valve, guide and rotator			
- Exhaust valve seat			
- Exhaust valve, guide and rotator			
Piston crown, including recondition			
Piston skirt			
- Piston skirt/crown dismantling one	20000	16000	12000
- Piston skirt/crown dismantling all	32000	28000	24000
Piston rings			
Cylinder liner	20000	16000	12000
Antipolishing ring			
Gudgeon pin, inspection	20000	16000	12000
Gudgeon pin bearing, inspection	20000	16000	12000
Big end bearing			
- Big end bearing, inspection of one	20000	16000	12000
- Big end bearing, replacement of all	36000	36000	36000
Main bearing			
- Main bearing, inspection of one	20000	16000	12000
- Main bearing, replacement of all	36000	36000	36000
Camshaft bearing			
- Camshaft bearing, inspection of one	36000	36000	36000
- Camshaft bearing, replacement of all	60000	60000	60000
Turbocharger inspection, cleaning	12000	12000	12000
Charge air cooler	6000	6000	6000
Rubber elements for flexible mounting			

Figure A.11: Time between overhauls and inspection for Wärtsilä 46F (Wärtsilä, 2019c)

Component	Expected life time (h)		
	LFO operation	HFO1 operation	HFO2 operation
Twin pump fuel injection			
- Injection nozzle	6000	6000	6000
- Injection pump element	24000	24000	24000
Cylinder head	60000	60000	60000
- Inlet valve seat	36000	36000	36000
- Inlet valve, guide and rotator	24000	24000	24000
- Exhaust valve seat	36000	36000	36000
- Exhaust valve, guide and rotator	20000	16000	12000
Piston crown, including recondition	36000	36000	36000
Piston skirt	60000	60000	60000
- Piston skirt/crown dismantling one			
- Piston skirt/crown dismantling all			
Piston rings	20000	16000	12000
Cylinder liner	60000	60000	60000
Antipolishing ring	20000	16000	12000
Gudgeon pin, inspection	60000	60000	60000
Gudgeon pin bearing, inspection	36000	36000	36000
Big end bearing	36000	36000	36000
- Big end bearing, inspection of one			
- Big end bearing, replacement of all			
Main bearing	36000	36000	36000
- Main bearing, inspection of one			
- Main bearing, replacement of all			
Camshaft bearing	60000	60000	60000
- Camshaft bearing, inspection of one			
- Camshaft bearing, replacement of all			
Turbocharger inspection, cleaning			
Charge air cooler	36000	36000	36000
Rubber elements for flexible mounting	60000	60000	60000

Figure A.12: Components expected life time Wärtsilä 46F (Wärtsilä, 2019c)

A.4 Electronic Systems

A.4.1 ’As Is’ Condition

ELECTRONIC SYSTEM CONDITION - STAGE 1 ’AS IS’ Condition

Overall Condition	Definition
Good	System is behaving well and working according to specifications
Average - Further Inspection to be Defined	Average performance and inspections is needed to identify the issues
Average - Unknown Status of the System	System not in use and performance not known
Upgrades Required	System is working OK but already requires upgrades
Bad	System is working badly and not performing according to design specs

Table A.2 continued from previous page

ELECTRONIC SYSTEM CONDITION - STAGE 1 'AS IS' Condition	
Obsolete	System is obsolete and needs replacement

Design Life	Input from Design Specifications - Number

Refurbishments	Definitions
Yes	System components have been refurbished during operating life
No	System components have not been refurbished during operating life

Degree of Refurbishments	Definition
Low	1-5% of Components have been refurbished during operating life
Moderate	6-10 % of Components have been refurbished during operating life
Considerable	11-25% of Components have been refurbished during operating life
High	50%+ of Components have been refurbished during operating life
Extreme	70%+ of Components have been refurbished during operating life

Replacements	Definition
Yes	System components have been replaced during operating life
No	System components have not been replaced during operating life

Degree of Replacements	Definition
Low	1-5% of Components have been replaced during operating life
Moderate	6-10 % of Components have been replaced during operating life
Considerable	11-25% of Components have been replaced during operating life
High	50%+ of Components have been replaced during operating life
Extreme	70%+ of Components have been replaced during operating life

Failure and Incident	Definition
None	No component has failed/had incident during operating life
Low	1-5% of Components have failed/had incident during operating life
Moderate	6-10% of Components have failed/had incident during operating life
High	11-20% of Components have failed/had incident during operating life
Extreme	20%+ of Components have failed/had incident during operating life

Maintenance	Definition
Maintained according to STAR	System is being maintained according to guidelines
Not Maintained	System is not being maintained
Backlog in Maintenance	Maintenance Backlog - List of work that needs to be completed

Table A.2: Definition of Concepts for Stage 1: 'AS IS' Condition Analysis.

A.4.2 Software Analysis

ELECTRONIC SYSTEM CONDITION - STAGE 2 Software Analysis

Overall Condition	Definition
Good	Software is performing well and no issues are found
Average	Software performance is average, experiencing some issues during operation

Table A.3 continued from previous page

ELECTRONIC SYSTEM CONDITION - STAGE 2 Software Analysis	
Upgrades Required	Software performance is bad and not working accordingly during operation
Bad	Software is already obsolete with integration issues with other updated software
Obsolete	System is obsolete and needs replacement

Failure Rates per Year	Definition
Low	0.0 - 0.1 Failures per year
Moderate	0.1 - 0.5 Failures per year
Considerable	0.5 - 1.0 Failures per year
High	1.0 - 2.0 Failures per year
Extreme	2.0+ Failures per year

Process Data Analysis and Transfer Capability	**Definition**
Low	Few outputs being exchanged
Moderate	Moderate amount of outputs being exchanged
Considerable	Considerable amount of outputs being exchanged
High	High amount of outputs being exchanged
Extreme	Extreme amount of outputs being, i.e. System completely dependent of each other

Integration Complexity SAS/ICSS	**Definition**
Low	Software with very few dependent inputs, easy to solve integration problems
Moderate	Software with moderate dependent inputs, moderate work to solve integration problems
Considerable	Software with considerable dependent inputs, problematic but manageable to solve integration problems
High	Software with high dependent inputs, problematic and hard to solve integration problems
Extreme	Software totally dependent from one another, impossible to work without integrated outputs

Software Updates (LE Period)	**Definition**
None	No updates will be required during LE Period
Minor	Minor updates will be required during LE Period
Major	Major updates will be required During LE Period
Obsolete	The software will be completely obsolete

Software Company (LE Period)	**Definition**
Major - Open	Well established provider most probable to open and running during LE period
Major - Closed	Big company with many employees but probable to be closed during LE period

Table A.3 continued from previous page

ELECTRONIC SYSTEM CONDITION - STAGE 2 Software Analysis	
Minor - Open	Small company but with good possibilities of being open during LE period
Minor - Closed	Small company, probably closed during LE period

Support Availability (LE Period)	Definition
High	Easy to find support for software
Moderate	Moderate issues when finding support for software
Low	Hard to find support for software
Not-Available	Not possible to find support for software

Human Competence (LE Period)	Definition
Available	Good availabitility of competent personnel to operate the system
Moderate	Moderate availability of workforce
Limited	Limited availabity of workforce
Not-Available	No availability of personnel to operate the system

Compliance with Rules and Regulations (LE Period)	Definition
Compliant - None to Low Efforts	Compliance is achieved without major work or changes
Compliant - Moderate Efforts	Compliance is achieved with moderate levels of work and changes
Compliant - High Efforts	Compliance is achieved with high levels of work and changes
Not Compliant	Compliance is not achieved

Table A.3: Definition of Concepts for Stage 2:Software Analysis.

A.4.3 Hardware Analysis

ELECTRONIC SYSTEM CONDITION - STAGE 2 Software Analysis	

Overall Condition	Definition
Good	Software is performing well and no issues are found
Average	Software performance is average, experiencing some issues during operation
Upgrades Required	Software performance is bad and not working accordingly during operation
Bad	Software is already obsolete with integration issues with other updated software
Obsolete	System is obsolete and needs replacement

Failure Rates per Year	Definition
Low	0.0 - 0.1 Failures per year
Moderate	0.1 - 0.5 Failures per year
Considerable	0.5 - 1.0 Failures per year
High	1.0 - 2.0 Failures per year
Extreme	2.0+ Failures per year

Support Availability (LE Period)	Definition
High	Easy to find support for software

Table A.4 continued from previous page

ELECTRONIC SYSTEM CONDITION - STAGE 2 Software Analysis	
Moderate	Moderate issues when finding support for software
Low	Hard to find support for software
Not-Available	Not possible to find support for software

Spare Parts Availability (LE Period)	Definition
Yes	Spare parts will be easy to find
No	Spare parts will be hard to find

Obsoluteness Status (LE Period)	Definition
Obsolete	Compliance is achieved without major work or changes
Not Obsolete	Compliance is achieved with moderate levels of work and changes

Compliance with Rules and Regulations (LE Period)	Definition
Compliant - None to Low Efforts	Compliance is achieved without major work or changes
Compliant - Moderate Efforts	Compliance is achieved with moderate levels of work and changes
Compliant - High Efforts	Compliance is achieved with high levels of work and changes
Not Compliant	Compliance is not achieved

Table A.4: Definition of Concepts for Stage 3: Hardware Analysis.

Appendix B

FPSO Description

B.1 Regression Analysis

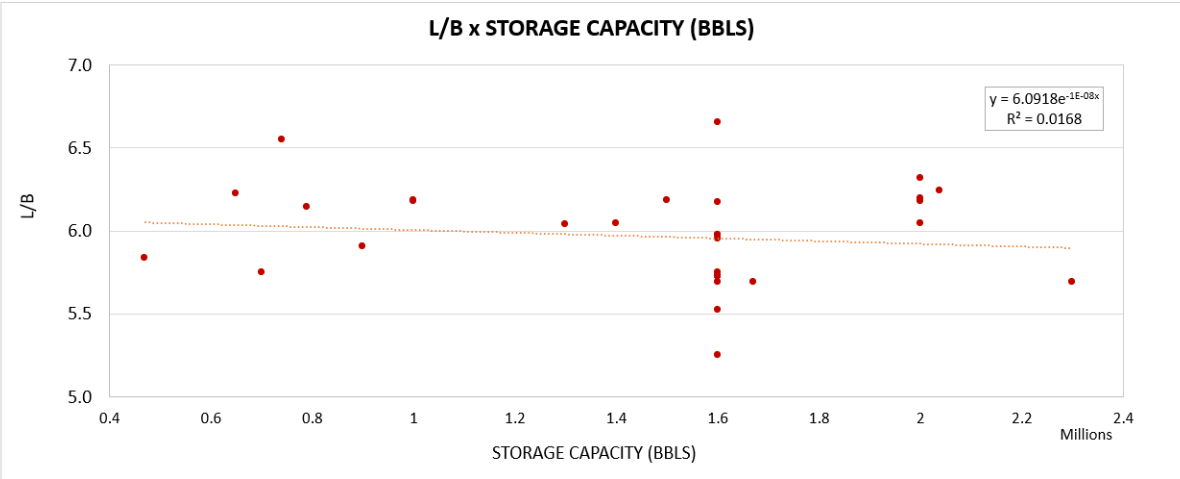


Figure B.1: Regression Analysis Ratios L/B x Storage Capacity.

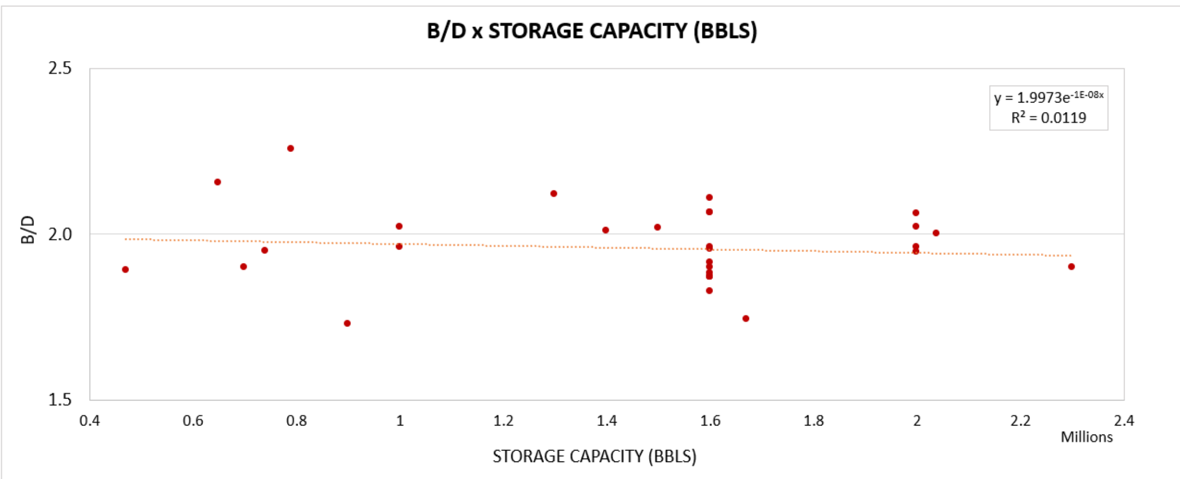


Figure B.2: Regression Analysis Ratios B/D x Storage Capacity.

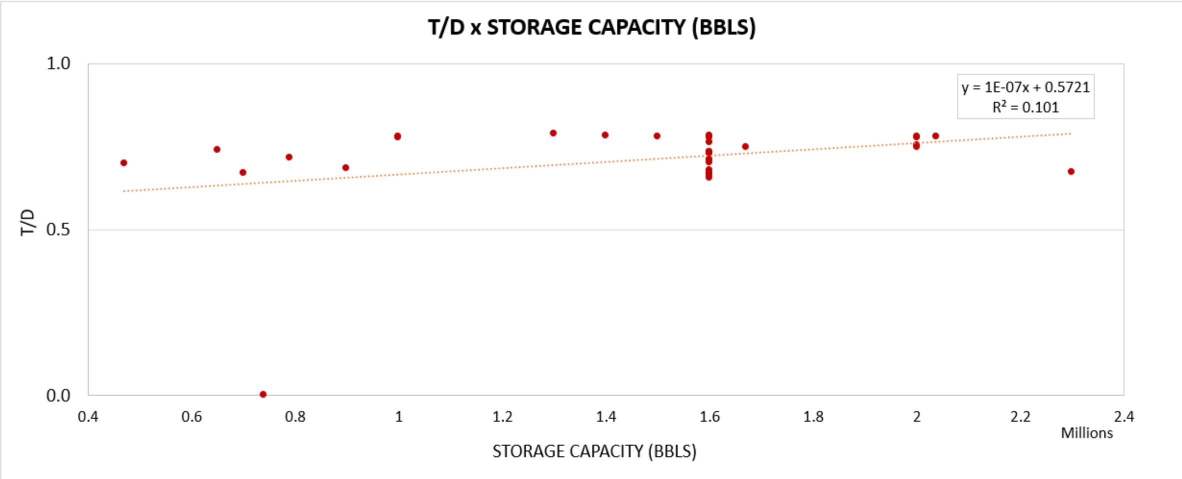


Figure B.3: Regression Analysis Ratios T/D x Storage Capacity.

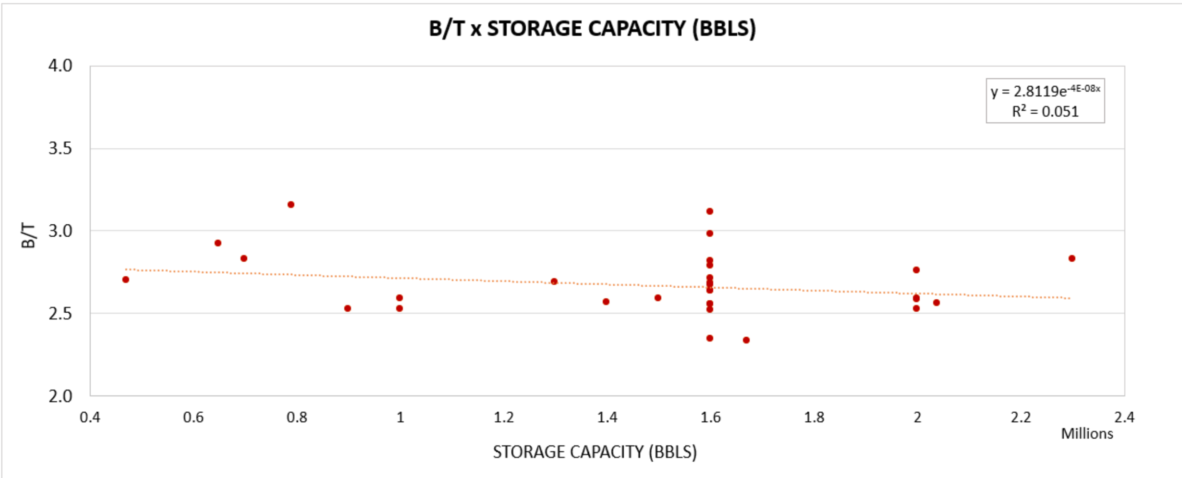


Figure B.4: Regression Analysis Ratios B/T x Storage Capacity.

B.2 Structural Arrangement

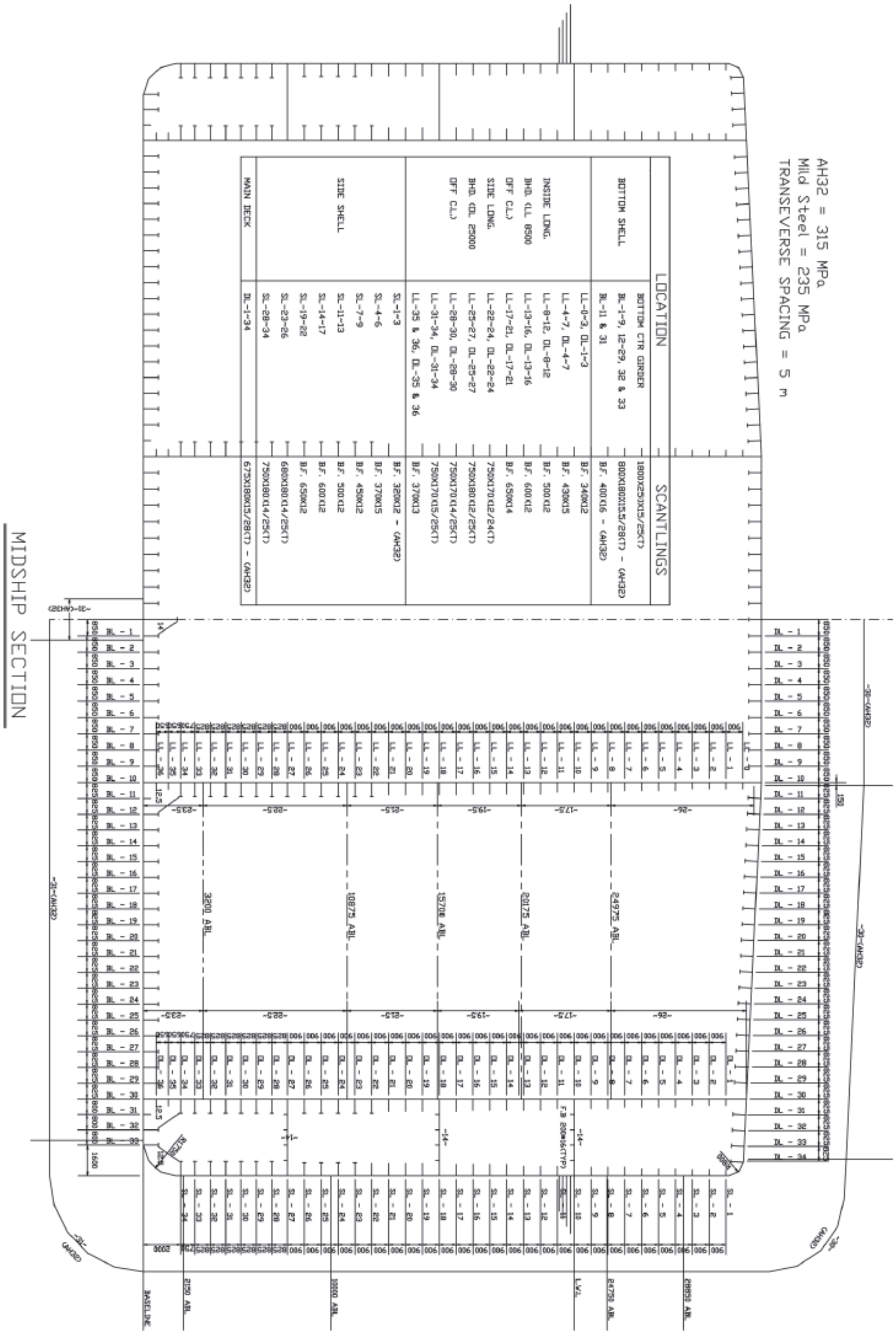


Figure B.5: Structural Arrangement from Paik et al. (2004).

B.3 Overhauls and Replacements.

Component	Maintenance interval (h) LFO/GAS operation	Expected lifetime (h) LFO/GAS operation	Maintenance interval (h) LFO/HFO operation	Expected life time (h) LFO/HFO operation
- Big end bearing	20000	36000	16000	36000
- Cylinder head	18000...20000	60000...72000	12000 (HFO2) 16000 (HFO1)	60000
- Cylinder liner	24000	180000	16000	180000
- Exhaust valve	12000...18000	36000	12000...18000	12000...18000
- Inj. valve complete [2]) [3])	8000	32000		
- Injection nozzles [1])	8000	8000	8000	8000
- Injection pump (Twin Pump)	-	-	12000 (HFO2) 16000 (HFO1) 20000 (LFO)	24000
- Injection pump, pilot	24000	24000	24000	24000
- Inlet valve	12000...18000	36000	12000...18000	24000
- Main bearing	24000	36000	24000	36000
- Main gas admission valve	18000	18000	-	-
- Piston	24000 [1]) / 48000 [2])	120000	16000 [1]) / 24000 [2])	36000
- Piston rings	24000	24000	16000	16000

Figure B.6: Wärtsilä 46DF Components, Overhauls and Expected Life Wärtsilä (2019b).

Component	Expected Technical Life Times (h)		
	MDF	HFO1 [1)]	HFO2 [1)]
Piston crown	60000	48000	42000
Piston rings	20000	14000	10000
Cylinder liner	80000	60000	48000
Cylinder head	60000	56000	50000
Inlet valve and valve seat insert	40000	42000	30000
Exhaust valve and valve seat insert	40000	28000 [2)]	20000
Injection valve nozzle	4000	4000	4000
Injection pump element	28000	28000	20000
Main bearing	60000	48000	42000
Big end bearing	20000	20000	20000

Component	Time between inspection or overhaul (h)		
	MDF	HFO1 [1)]	HFO2 [1)]
Piston crown	20000	14000	10000
Piston rings	20000	14000	10000
Cylinder liner	20000	14000	10000
Cylinder head	20000	14000	10000
Inlet valve and valve seat insert	20000	14000	10000
Exhaust valve and valve seat insert	20000	14000	10000
Injection valve nozzle	4000	4000	4000
Injection pump element	20000	14000	10000
Main bearing	20000	14000	10000
Big end bearing	20000	14000	10000

Figure B.7: Wärtsilä 20 Components, Overhauls and Expected Life (Wärtsilä, 2019a).

Appendix **C**

Case Study

C.1 General Asset Condition

SFI System Number	System Name	Information Source	Usage	Usage Status	Maintenance	Condition	Obsolete	Comments	Date
20	Hull materials, general hull work	Personnel Experience	InService	Working According to Specs	Maintained according to Maintenance Software	Good	No		13/05/2020
21	Afterbody	Personnel Experience	InService	Working According to Specs	Maintained according to Maintenance Software	Good	No		13/05/2020
22	Engine area	Personnel Experience	InService	Working According to Specs	Maintained according to Maintenance Software	Good	No		13/05/2020
23	Cargo area - hull small vessels	Maintenance Software	InService	Working According to Specs	Maintained according to Maintenance Software	Good	No		13/05/2020
24	Forebody	Personnel Experience	InService	Working According to Specs	Maintained according to Maintenance Software	Good	No		13/05/2020
25	Deck houses and superstructures	Maintenance Software	InService	Working According to Specs	NOT Maintained	Bad	No		13/05/2020
26	Hull outfitting	Personnel Experience	InService	Working According to Specs	Maintained according to Maintenance Software	Good	No		13/05/2020
27	Material protection, external	Personnel Experience	InService	Working According to Specs	NOT Maintained	Average - Further Inspection to be Defined	No		13/05/2020
28	Material protection, internal	Personnel Experience	InService	Working According to Specs	NOT Maintained	Average - Further Inspection to be Defined	No		13/05/2020
30	Hatches, ports	Maintenance Software	InService	Working According to Specs	Maintained according to Maintenance Software	Good	No		13/05/2020
31	Equipment for cargo in holds/on deck	Personnel Experience	InService	Working According to Specs	Maintained according to Maintenance Software	Good	No		13/05/2020
32	Special cargo handling equipment	Personnel Experience	InService	Working According to Specs	Maintained according to Maintenance Software	Good	No		13/05/2020
33	Deck cranes for cargo	Vendor	InService	Working According to Specs	Maintained according to Maintenance Software	Good	No		13/05/2020
35	Loading/discharging systems for liquid cargo	RBI	InService	Working According to Specs	Maintained according to Maintenance Software	Good	No		13/05/2020
36	Freezing, refrigerating, heating systems for cargo	RBI	InService	Working Below Specs	Maintained according to Maintenance Software	Average - Known Status of the System	No		13/05/2020
37	Gas/ventilation systems for cargo holds/tanks	Personnel Experience	InService	Working Below Specs	Maintained according to Maintenance Software	Upgrades Required	No		13/05/2020
38	Auxiliary systems, equipment for cargo	Personnel Experience	InService	Working Below Specs	NOT Maintained	Upgrades Required	No		13/05/2020
40	Manoeuvring machinery, equipment	Personnel Experience	InService	Working According to Specs	Maintained according to Maintenance Software	Good	No		13/05/2020
41	Navigation, searching equipment	Vendor	InService	Working According to Specs	Maintained according to Maintenance Software	Average - Known Status of the System	No		13/05/2020
42	Communication equipment	Vendor	InService	Working According to Specs	Maintained according to Maintenance Software	Average - Known Status of the System	No		13/05/2020
43	Anchoring, mooring, towing equipment	Maintenance Software	InService	Working According to Specs	Maintained according to Maintenance Software	Average - Known Status of the System	No		13/05/2020
44	Rep./maint./clean. equip. workshop/store outfit, name plates	Maintenance Software	InService	Working Below Specs	NOT Maintained	Bad	No		13/05/2020
45	Lifting, transport equipment for machinery components	Maintenance Software	InService	Working Below Specs	NOT Maintained	Bad	No		13/05/2020
50	Lifesaving, protection, medical equipment	Vendor	InService	Working According to Specs	Maintained according to Maintenance Software	Good	No		13/05/2020
51	Insulation, panels, bulkheads, doors, sidescuttles,skylights	Maintenance Software	InService	Working According to Specs	NOT Maintained	Good	No		13/05/2020
52	Internal deck covering, ladders, steps, railing	Maintenance Software	InService	Working According to Specs	NOT Maintained	Good	No		13/05/2020
53	Ext. deck covering, ladders, steps, fore, aft gangway	Maintenance Software	InService	Working According to Specs	NOT Maintained	Good	No		13/05/2020
54	Furniture, inventory, entertainment equipment	Maintenance Software	InService	Working According to Specs	Maintained according to Maintenance Software	Good	No		13/05/2020

Figure C.1: Fictional FPSO General Condition 1.

SFI System Number	System Name	Information Source	Usage	Usage Status	Maintenance	Condition	Obsolete	Comments	Date
55	Galley/pantry equip., provision plants, laundry/irc	Maintenance Software	InService	Working According to Specs	Maintained according to Maintenance Software	Good	No		13/05/2020
56	Transport equipment for crew, passengers, provis	Maintenance Software	InService	Working Below Specs	Maintained according to Maintenance Software	Average - Further Inspection to be Defined	No		13/05/2020
57	Ventilation, air-conditioning, heating systems	RBI	InService	Broken	NOT Maintained	Bad	No		13/05/2020
58	Sanitary syst. w/discharges, accommodation drai	RBI	InService	Working Below Specs	NOT Maintained	Upgrades Required	No		13/05/2020
59	Passenger vessel cabins, public rooms	Maintenance Software	InService	Working According to Specs	Maintained according to Maintenance Software	Good	No		13/05/2020
60	Diesel engines for propulsion	Vendor	InService	Working According to Specs	Maintained according to Maintenance Software	Good	No		13/05/2020
65	Motor aggregates for main electric power produc	Personnel Experience	InService	Working According to Specs	Maintained according to Maintenance Software	Good	No		13/05/2020
66	Other aggr., gen. for main, emergency el. power p	Personnel Experience	InService	Working According to Specs	Maintained according to Maintenance Software	Good	No		13/05/2020
70	Fuel systems	RBI	InService	Working According to Specs	Maintained according to Maintenance Software	Good	No		13/05/2020
71	Lube oil systems	RBI	InService	Working According to Specs	Maintained according to Maintenance Software	Good	No		13/05/2020
72	Cooling systems	Personnel Experience	InService	Working According to Specs	Maintained according to Maintenance Software	Good	No		13/05/2020
73	Compressed air systems	Personnel Experience	InService	Working According to Specs	Maintained according to Maintenance Software	Good	No		13/05/2020
74	Exhaust systems, air intakes	Maintenance Software	InService	Working According to Specs	Maintained according to Maintenance Software	Good	No		13/05/2020
75	Steam, condensate, feed water systems	Maintenance Software	InService	Working According to Specs	Maintained according to Maintenance Software	Good	No		13/05/2020
76	Distilled, make-up water systems	Maintenance Software	InService	Working According to Specs	Maintained according to Maintenance Software	Good	No		13/05/2020
79	Automation systems for machinery	Maintenance Software	InService	Working According to Specs	Maintained according to Maintenance Software	Good	No		13/05/2020
80	Ballast, bilge systems, gutter pipes outside accom	Maintenance Software	InService	Working Below Specs	Maintained according to Maintenance Software	Average - Known Status of the System	No		13/05/2020
81	Fire, lifeboat alarm, fire fighting and wash down s	Maintenance Software	InService	Working Below Specs	Maintained according to Maintenance Software	Average - Known Status of the System	No		13/05/2020
82	Air, sounding systems from tanks to deck	Personnel Experience	InService	Working Below Specs	Maintained according to Maintenance Software	Average - Known Status of the System	No		13/05/2020
83	Special common hydraulic oil systems	RBI	InService	Working According to Specs	Maintained according to Maintenance Software	Good	No		13/05/2020
84	Central heat transfer systems w/chemical fluids/	Maintenance Software	InService	Broken	Backlog Maintenance	Upgrades Required	Yes		13/05/2020
85	Common electric, electronic systems	Personnel Experience	InService	Working Below Specs	Backlog Maintenance	Bad	Yes		13/05/2020
86	Electric power supply	Maintenance Software	InService	Working Below Specs	Maintained according to Maintenance Software	Good	No		13/05/2020
87	Common electric distribution systems	Maintenance Software	InService	Working According to Specs	Maintained according to Maintenance Software	Good	No		13/05/2020
88	Electric cable installation	Maintenance Software	InService	Working Below Specs	Backlog Maintenance	Upgrades Required	Yes		13/05/2020
89	Electric consumer systems	Maintenance Software	InService	Working According to Specs	Maintained according to Maintenance Software	Good	No		13/05/2020

Figure C.2: Fictional FPSO General Condition 2.

SFI System Number	System Name	Expected Scope	Critical Spare Parts?	Type of Work	Scope Location
20	Hull materials, general hull work	Normal Maintenance		Renewal	Drydock Required
21	Afterbody	Normal Maintenance		Renewal	Drydock Required
22	Engine area	Normal Maintenance		Renewal	Drydock Required
23	Cargo area - hull small vessels	Normal Maintenance		Life Extension	Drydock Required
24	Forebody	Normal Maintenance		Renewal	Yard stay
25	Deck houses and superstructures	Renewal of steel and recoating		Life Extension	Yard stay
26	Hull outfitting	Normal Maintenance		Life Extension	Yard stay
27	Material protection, external	Replacement of anodes and recoating		Life Extension	Drydock Required
28	Material protection, internal	Replacement of anodes and recoating		Life Extension	Yard stay
30	Hatches, ports	Normal Maintenance		Life Extension	Yard stay
31	Equipment for cargo in holds/on deck	Normal Maintenance		Life Extension	Included in Maintenance Program
32	Special cargo handling equipment	Normal Maintenance		Life Extension	Included in Maintenance Program
33	Deck cranes for cargo	Normal Maintenance		Renewal	Included in Maintenance Program
35	Loading/discharging systems for liquid cargo	Normal Maintenance		Renewal	Offshore campaign requiring process shutdown
36	Freezing, refrigerating, heating systems for cargo	More Inspections are requied to define actual condition		Life Extension	Included in Maintenance Program
37	Gas/ventilation systems for cargo holds/tanks	Some areas will require upgrades		Life Extension	Offshore campaign requiring process shutdown
38	Auxiliary systems, equipment for cargo	Some of the equipment needs to be replaced		Life Extension	Offshore campaign requiring process shutdown
40	Manoeuvring machinery, equipment	Normal Maintenance		Life Extension	Included in Maintenance Program
41	Navigation, searching equipment	Some of the equipment will need to be replaced	YES	Life Extension	Included in Maintenance Program
42	Communication equipment	Some of the equipment will need to be replaced	YES	Life Extension	Included in Maintenance Program
43	Anchoring, mooring, towing equipment	Mooring system needs a full inspection and possible replacement			Included in Maintenance Program
44	Rep./maint./clean. equip. workshop/store outfit, name plates	New equipment are necessary		Renewal	Included in Maintenance Program
45	Lifting, transport equipment for machinery components	New equipment are necessary		Renewal	Included in Maintenance Program
50	Lifesaving, protection, medical equipment	Normal Maintenance		Renewal	Included in Maintenance Program
51	Insulation, panels, bulkheads, doors, sidescuttles,skylights	Normal Maintenance		Renewal	Yard stay
52	Internal deck covering, ladders, steps, railing	Normal Maintenance		Life Extension	Included in Maintenance Program
53	Ext. deck covering, ladders, steps, fore, aft gangway	Normal Maintenance		Life Extension	Included in Maintenance Program
54	Furniture, inventory, entertainment equipment	Normal Maintenance		Life Extension	Included in Maintenance Program

Figure C.3: Fictional FPSO General Scope 1.

SFI System Number	System Name	Expected Scope	Critical Spare Parts?	Type of Work	Scope Location
55	Galley/pantry equip., provision plants, laundry/irc	Normal Maintenance		Life Extension	Included in Maintenance Program
56	Transport equipment for crew, passengers, provis	Replacement of some equipment		Life Extension	Included in Maintenance Program
57	Ventilation, air-conditioning, heating systems	Full replacement in some areas are required		Life Extension	Included in Maintenance Program
58	Sanitary syst. w/discharges, accommodation drai	Upgrades in some areas are required		Life Extension	Included in Maintenance Program
59	Passenger vessel cabins, public rooms	Normal Maintenance		Life Extension	Included in Maintenance Program
60	Diesel engines for propulsion	Normal Maintenance		Life Extension	Offshore campaign requiring process shutdown
65	Motor aggregates for main electric power produc	Normal Maintenance		Life Extension	Offshore campaign requiring process shutdown
66	Other aggr., gen. for main, emergency el. power p	Normal Maintenance		Life Extension	Offshore campaign requiring process shutdown
70	Fuel systems	Normal Maintenance		Life Extension	Included in Maintenance Program
71	Lube oil systems	Normal Maintenance		Life Extension	Included in Maintenance Program
72	Cooling systems	Normal Maintenance		Renewal	Included in Maintenance Program
73	Compressed air systems	Normal Maintenance		Renewal	Included in Maintenance Program
74	Exhaust systems, air intakes	Normal Maintenance		Life Extension	Included in Maintenance Program
75	Steam, condensate, feed water systems	Normal Maintenance		Life Extension	Included in Maintenance Program
76	Distilled, make-up water systems	Normal Maintenance		Life Extension	Included in Maintenance Program
79	Automation systems for machinery	Normal Maintenance		Life Extension	Included in Maintenance Program
80	Ballast, bilge systems, gutter pipes outside accom	Replacement of some subsystems		Life Extension	Included in Maintenance Program
81	Fire, lifeboat alarm, fire fighting and wash down s	Replacement and upgrades		Life Extension	Included in Maintenance Program
82	Air, sounding systems from tanks to deck	More Inspections are requied to define actual condition		Life Extension	Included in Maintenance Program
83	Special common hydraulic oil systems	Normal Maintenance		Life Extension	Included in Maintenance Program
84	Central heat transfer systems w/chemical fluids/	Some of the equipment needs to be replaced		Renewal	Offshore campaign requiring process shutdown
85	Common electric, electronic systems	Full replacement in some areas are required		Renewal	Offshore campaign requiring process shutdown
86	Electric power supply	Normal Maintenance		Renewal	Offshore campaign requiring process shutdown
87	Common electric distribution systems	Normal Maintenance		Renewal	Included in Maintenance Program
88	Electric cable installation	Full upgrade of electric cables in most areas		Renewal	Offshore campaign requiring process shutdown
89	Electric consumer systems	Normal Maintenance		Renewal	Included in Maintenance Program

Figure C.4: Fictional FPSO General Scope 2.

C.2 Structural Assessment

C.2.1 'AS IS' Condition

ID	ELEMENT	INFORMATION SOURCE	USAGE	USAGE STATUS	MAINTENANCE	CONDITION	OBSOLETE	EXPECTED SCOPE	TYPE OF WORK	CRITICAL SPARE PARTS	SCOPE LOCATION
1	Overall Bottom Deck Midship	Maintenance Software	InService	Working According to Specifications	Not Maintained	Average - Further Inspection to be Defined	NO	Reinforcement of steel plates and stiffeners, as well as recoating	Life Extension	NO	Yard Stay
2	PBT	Maintenance Software	InService	Working According to Specifications	Not Maintained	Average - Further Inspection to be Defined	NO	Reinforcement of steel plates and stiffeners, as well as recoating	Life Extension	NO	Yard Stay
2	SBT	Maintenance Software	InService	Working According to Specifications	Not Maintained	Average - Further Inspection to be Defined	NO	Reinforcement of steel plates and stiffeners, as well as recoating	Life Extension	NO	Yard Stay
2	PCT	Maintenance Software	InService	Working According to Specifications	Not Maintained	Average - Further Inspection to be Defined	NO	Reinforcement of steel plates and stiffeners, as well as recoating	Life Extension	NO	Yard Stay
2	SCT	Maintenance Software	InService	Working According to Specifications	Not Maintained	Average - Further Inspection to be Defined	NO	Reinforcement of steel plates and stiffeners, as well as recoating	Life Extension	NO	Yard Stay
2	CCT	Maintenance Software	InService	Working According to Specifications	Not Maintained	Average - Further Inspection to be Defined	NO	Reinforcement of steel plates and stiffeners, as well as recoating	Life Extension	NO	Yard Stay
1	Port Side Shell - Outside Hull	Maintenance Software	InService	Working According to Specifications	Not Maintained	Average - Further Inspection to be Defined	NO	Reinforcement of steel plates and stiffeners, as well as recoating	Life Extension	NO	Drydock Required
2	PBT	Maintenance Software	InService	Working According to Specifications	Not Maintained	Average - Further Inspection to be Defined	NO	Reinforcement of steel plates and stiffeners, as well as recoating	Life Extension	NO	Drydock Required
1	Starboard Side Shell - Outside Hull	Maintenance Software	InService	Working According to Specifications	Not Maintained	Average - Further Inspection to be Defined	NO	Reinforcement of steel plates and stiffeners, as well as recoating	Life Extension	NO	Drydock Required
2	SBT	Maintenance Software	InService	Working According to Specifications	Not Maintained	Average - Further Inspection to be Defined	NO	Reinforcement of steel plates and stiffeners, as well as recoating	Life Extension	NO	Drydock Required
1	Main Process Deck Shell	Maintenance Software	InService	Working According to Specifications	Maintained	Good	NO	Regular Maintenance	Life Extension	NO	Yard Stay
2	PBT	Maintenance Software	InService	Working According to Specifications	Maintained	Good	NO	Regular Maintenance	Life Extension	NO	Yard Stay
2	SBT	Maintenance Software	InService	Working According to Specifications	Maintained	Good	NO	Regular Maintenance	Life Extension	NO	Yard Stay
2	PCT	Maintenance Software	InService	Working According to Specifications	Maintained	Good	NO	Regular Maintenance	Life Extension	NO	Yard Stay
2	SCT	Maintenance Software	InService	Working According to Specifications	Maintained	Good	NO	Regular Maintenance	Life Extension	NO	Yard Stay
2	CCT	Maintenance Software	InService	Working According to Specifications	Maintained	Good	NO	Regular Maintenance	Life Extension	NO	Yard Stay
1	Accommodation Block	Maintenance Software	InService	Working According to Specifications	Maintained	Good	NO	Regular Maintenance	Life Extension	NO	Normal Maintenace
2	Windows	Maintenance Software	InService	Working According to Specifications	Maintained	Good	NO	Regular Maintenance	Life Extension	NO	Normal Maintenace
2	Inside Decks	Maintenance Software	InService	Working According to Specifications	Maintained	Good	NO	Regular Maintenance	Life Extension	NO	Normal Maintenace
2	External Accomodation Walls	Maintenance Software	InService	Working According to Specifications	Not Maintained	Bad	NO	Regular Maintenance	Life Extension	NO	Normal Maintenance
2	Internal Accomodation Walls	Maintenance Software	InService	Working According to Specifications	Maintained	Good	NO	Regular Maintenance	Life Extension	NO	Normal Maintenance
2	Process Deck Level Plate	Maintenance Software	InService	Working According to Specifications	Not Maintained	Average - Further Inspection to be Defined	NO	Reinforcement of steel plates and stiffeners, as well as recoating	Life Extension	NO	Normal Maintenance
1	Helideck	Maintenance Software	InService	Working According to Specifications	Maintained	Good	NO	Regular Maintenance	Life Extension	NO	Normal Maintenance
2	Helideck Supports	Maintenance Software	InService	Working According to Specifications	Maintained	Good	NO	Regular Maintenance	Life Extension	NO	Normal Maintenance
2	Helideck Deck	Maintenance Software	InService	Working According to Specifications	Maintained	Good	NO	Regular Maintenance	Life Extension	NO	Normal Maintenace
1	Flare Structure	Maintenance Software	InService	Working According to Specifications	Maintained	Good	NO	Regular Maintenance	Life Extension	NO	Normal Maintenace
2	Flare Deck Support	Maintenance Software	InService	Working According to Specifications	Maintained	Good	NO	Regular Maintenance	Life Extension	NO	Normal Maintenace

Figure C.5: Qualitative Assessment of Structural Components

C.2.2 Quantitative Model - Structural Systems

		Plate						
ID	Side	t_gross (mm)	Corrossion Allowance (mm)	k	t_renewal (mm)	Corrosion Rate (mm/year)	RUL Allowance (years)	RUL (years)
P/S BT G1	Side 1	30	3	0.80	24	0.15	26	45+
P/S BT G1	Side 2	26	3	0.80	20.8	0.15	26	40
P/S BT G1	Side 3	14	3	0.80	11.2	0.15	26	24
P/S BT G1	Side 4	17.5	3	0.80	14	0.15	26	29
P/S BT G2	Side 1	14	1.5	0.80	11.2	0.15	16	24
P/S BT G2	Side 2	17.5	1.5	0.80	14	0.15	16	29
P/S BT G2	Side 3	14	1.5	0.80	11.2	0.15	16	24
P/S BT G2	Side 4	17.5	1.5	0.80	14	0.15	16	29
P/S BT G3	Side 1	14	1.5	0.80	11.2	0.15	16	24
P/S BT G3	Side 2	21.5	1.5	0.80	17.2	0.15	16	34
P/S BT G3	Side 3	14	1.5	0.80	11.2	0.15	16	24
P/S BT G3	Side 4	21.5	1.5	0.80	17.2	0.15	16	34
P/S BT G4	Side 1	14	3	0.80	11.2	0.15	26	24
P/S BT G4	Side 2	22.5	3	0.80	18	0.15	26	36
P/S BT G4	Side 3	31	3	0.80	24.8	0.15	26	45+
P/S BT G4	Side 4	22.5	3	0.80	18	0.15	26	36
P/C/S CT G1	Side 1	30	2	0.80	24	0.025	45+	45+
P/C/S CT G1	Side 2	26	2	0.80	20.8	0.025	45+	45+
P/C/S CT G1	Side 4	26	2	0.80	20.8	0.025	45+	45+
P/C/S CT G2	Side 2	17.5	1	0.80	14	0.025	45+	45+
P/C/S CT G2	Side 4	17.5	1	0.80	14	0.025	45+	45+
P/C/S CT G3	Side 2	19.5	1	0.80	15.6	0.025	45+	45+
P/C/S CT G3	Side 4	19.5	1	0.80	15.6	0.025	45+	45+
P/C/S CT G4	Side 2	21.5	1	0.80	17.2	0.025	45+	45+
P/C/S CT G4	Side 4	21.5	1	0.80	17.2	0.025	45+	45+
P/C/S CT G5	Side 2	22.5	1	0.80	18	0.025	45+	45+
P/C/S CT G5	Side 4	22.5	1	0.80	18	0.025	45+	45+
P/C/S CT G6	Side 2	23.5	2	0.80	18.8	0.025	45+	45+
P/C/S CT G6	Side 3	31	2	0.80	24.8	0.025	45+	45+
P/C/S CT G6	Side 4	23.5	2	0.80	18.8	0.025	45+	45+

Figure C.6: Quantitative Assessment - Structural Plates.

		Stiffenner						
ID	Side	t_gross (mm)	Corrossion Allowance (mm)	k	t_renewal (mm)	Corrosion Rate (mm/year)	RUL Allowance (years)	RUL (years)
P/S BT G1	Side 1	25.00	3.00	0.75	18.75	0.15	26.00	45+
P/S BT G1	Side 2	12.00	3.00	0.75	9.00	0.15	26.00	26.00
P/S BT G1	Side 3	16.00	3.00	0.75	12.00	0.15	26.00	32.00
P/S BT G1	Side 4	12.00	3.00	0.75	9.00	0.15	26.00	26.00
P/S BT G2	Side 1	16.00	1.50	0.75	12.00	0.15	16.00	32.00
P/S BT G2	Side 2	12.00	1.50	0.75	9.00	0.15	16.00	26.00
P/S BT G2	Side 3	16.00	1.50	0.75	12.00	0.15	16.00	32.00
P/S BT G2	Side 4	12.00	1.50	0.75	9.00	0.15	16.00	26.00
P/S BT G3	Side 1	16.00	1.50	0.75	12.00	0.15	16.00	32.00
P/S BT G3	Side 2	12.00	1.50	0.75	9.00	0.15	16.00	26.00
P/S BT G3	Side 3	16.00	1.50	0.75	12.00	0.15	16.00	32.00
P/S BT G3	Side 4	12.00	1.50	0.75	9.00	0.15	16.00	26.00
P/S BT G4	Side 1	16.00	3.00	0.75	12.00	0.15	26.00	32.00
P/S BT G4	Side 2	12.50	3.00	0.75	9.38	0.15	26.00	26.00
P/S BT G4	Side 3	15.50	3.00	0.75	11.63	0.15	26.00	31.00
P/S BT G4	Side 4	12.00	3.00	0.75	9.00	0.15	26.00	26.00
P/C/S CT G1	Side 1	15	2	0.75	11.25	0.025	45+	45+
P/C/S CT G1	Side 2	-	2	-	-	0.025	-	-
P/C/S CT G1	Side 4	12	2	0.75	9	0.025	45+	45+
P/C/S CT G2	Side 2	-	1	-	-	0.025	-	-
P/C/S CT G2	Side 4	12	1	0.75	9	0.025	45+	45+
P/C/S CT G3	Side 2	-	1	-	-	0.025	-	-
P/C/S CT G3	Side 4	12	1	0.75	9	0.025	45+	45+
P/C/S CT G4	Side 2	-	1	-	-	0.025	-	-
P/C/S CT G4	Side 4	12	1	0.75	9	0.025	45+	45+
P/C/S CT G5	Side 2	-	1	-	-	0.025	-	-
P/C/S CT G5	Side 4	12	1	0.75	9	0.025	45+	45+
P/C/S CT G6	Side 2	-	2	-	-	0.025	-	-
P/C/S CT G6	Side 3	15.5	2	0.75	11.625	0.025	45+	45+
P/C/S CT G6	Side 4	12	2	0.75	9	0.025	45+	45+

Figure C.7: Quantitative Assessment - Structural Stiffeners.

C.2.3 Risk Analysis and Risk Mitigation

System		Functionality Description		Failure Description			Failure Effects			Risk Ranking		
REF	**System/Subsystem /Element**	**Function**	**Life Extension Assessment Outcome**	**Failure Cause or Mechanism**	**Failure Mode**	**Detection of Failure**	**Local Effects**	**Global Effect**	**Consequences**	**L**	**S**	**R**
1	Accomodation Block											
1.1.a	Windows	To allow for light and ventilation inside accommodation	Good condition, will need some replacement during LE period	Window glass in poor condition	Windows cracking and breaking	Inspecting windows	Room with open window	People have to be assigned to fix it	Some other maintenance task may have do be rescheduled	3	1	3
1.1.b	Windows	To allow for light and ventilation inside accommodation	Good condition, will need some replacement during LE period	Window glass in poor condition	Windows cracking and breaking	Inspecting windows	Room with open window	People have to be accommodate somewhere else	People have to be accommodate somewhere else	3	1	3
1.2	Inside Decks	They are thee floors of each deck level - sustain the loads and necessary accomodation equipment	Good condition, needs a few renewal and upgrades	*Regular Life Extension Work*	*Regular Life Extension Work*	*Regular Life Extension Work*	*Regular Life Extension Work*	*Regular Life Extension Work*	*Regular Life Extension Work*			
1.3.a	External Accomodation Walls	The external region that sustain all the components of the accomodation block	In bad condition, will require a full painting of the area	Excessive corrosion/damage in accommodation	Colapse of accomodation block	Regular Inspection	No place to accommodate crew	Suspention of production until problem is fixed	Loss of production days	3	5	15
1.3.b	External Accomodation Walls	The external region that sustain all the components of the accomodation block	In bad condition, will require a full painting of the area	Excessive corrosion/damage in accommodation	Colapse of some sections of accommodation	Regular Inspection	Some rooms break down	People have to be assigned to fix it	People have to be accommodate somewhere else	3	3	9
1.4	Internal Accomodation Walls	Internal walls dividing the accomodation regions	Good condition, needs a few renewal and upgrades	*Regular Life Extension Work*	*Regular Life Extension Work*	*Regular Life Extension Work*	*Regular Life Extension Work*	*Regular Life Extension Work*	*Regular Life Extension Work*			
1.5.a	Process Deck Level Plate	The 'floor' section where the accomodation is located in the external main deck area	Average condition, needs more inspection and possible upgrades duuring LE period	Excessive corrosion/damage in connection level between accommodation block and main deck	Colapse of accomodation block	Regular Inspection	Accommodation block is no longer safe - no place to accommodate crew	Suspention of production until problem is fixed	Loss of production days	2	5	10
1.5.b	Process Deck Level Plate	The 'floor' section where the accomodation is located in the external main deck area	Average condition, needs more inspection and possible upgrades duuring LE period	Excessive corrosion/damage in connection level between accommodation block and main deck	Cracking and breaking of some of the supporting section	Regular Inspection	Supporting region corroded	People have to be assigned to fix it	Some other maintenance task may have do be rescheduled	2	3	6
2	Flare											
2.1	Flare Deck Support	To support the flare system	Good condition, needs a few renewal and upgrades	*Regular Life Extension Work*	*Regular Life Extension Work*	*Regular Life Extension Work*	*Regular Life Extension Work*	*Regular Life Extension Work*	*Regular Life Extension Work*			
3	Helideck		Good condition, needs a few renewal and upgrades									
3.1	Helideck Supports	To sustain the helideck loads	Good condition, needs a few renewal and upgrades	*Regular Life Extension Work*	*Regular Life Extension Work*	*Regular Life Extension Work*	*Regular Life Extension Work*	*Regular Life Extension Work*	*Regular Life Extension Work*			
3.2	Helideck Deck	Flat region where the helicopter shall land	Good condition, needs a few renewal and upgrades	*Regular Life Extension Work*	*Regular Life Extension Work*	*Regular Life Extension Work*	*Regular Life Extension Work*	*Regular Life Extension Work*	*Regular Life Extension Work*			

Figure C.8: Structural System Risk Analysis P1.

System		Functionality Description		Failure Description			Failure Effects			Risk Ranking		
REF	**System/Subsystem /Element**	**Function**	**Life Extension Assessment Outcome**	**Failure Cause or Mechanism**	**Failure Mode**	**Detection of Failure**	**Local Effects**	**Global Effect**	**Consequences**	**L**	**S**	**R**
4	Midship Section											
4.1	Port Side Shell	To sustain the loads in the FPSO and hold ballast water	Average condition, needs more inspection and possible upgrades duuring LE period	Corrosion damage	Cracking due to corrosion effects	Regular Inspection	Minor damage in one region	Complete Structural Colapse	Asset sinking or capsizing	3	5	15
4.1.a	Ballast Tanks Plates	To sustain the loads in the FPSO and hold ballast water	First plate to need replacement in 8.9 years	Corrosion damage	Cracking due to corrosion effects	Regular Inspection	Minor damage in one region	Complete Structural Colapse	Asset sinking or capsizing	3	5	15
4.1.b	Ballast Tanks Stiffeners	To sustain the loads in the FPSO and hold ballast water	First stiffeners to need replacement in 7.6 years	Corrosion damage	Cracking due to corrosion effects	Regular Inspection	Minor damage in one region	Complete Structural Colapse	Asset sinking or capsizing	3	5	15
4.2	Starboard Side Shell	To sustain the loads in the FPSO and hold ballast water	Average condition, needs more inspection and possible upgrades duuring LE period	Corrosion damage	Cracking due to corrosion effects	Regular Inspection	Minor damage in one region	Complete Structural Colapse	Asset sinking or capsizing	3	5	15
4.2.a	Ballast Tanks Plates	To sustain the loads in the FPSO and hold ballast water	First plate to need replacement in 8.9 years	Corrosion damage	Cracking due to corrosion effects	Regular Inspection	Minor damage in one region	Complete Structural Colapse	Asset sinking or capsizing	3	5	15
4.2.b	Ballast Tanks Stiffeners	To sustain the loads in the FPSO and hold ballast water	First stiffeners to need replacement in 7.6 years	Corrosion damage	Cracking due to corrosion effects	Regular Inspection	Minor damage in one region	Complete Structural Colapse	Asset sinking or capsizing	3	5	15
4.3	Bottom Shell											
4.3.a	Port Ballast Tank Plate	To sustain the loads in the FPSO and hold ballast water	Further inspection is needed but first analysis does not show plate needing replacement during LE period	Corrosion damage	Cracking due to corrosion effects	Regular Inspection	Minor damage in one region	Complete Structural Colapse	Asset sinking or capsizing	1	5	5
4.3.b	Port Ballast Tank Stiffener	To sustain the loads in the FPSO and hold ballast water	Further inspection is needed and possible replacement of stiffeners in 9.6 years.	Corrosion damage	Cracking due to corrosion effects	Regular Inspection	Minor damage in one region	Complete Structural Colapse	Asset sinking or capsizing	3	5	15
4.3.c	Starboard Ballast Tank Plate	To sustain the loads in the FPSO and hold ballast water	Further inspection is needed but first analysis does not show plate needing replacement during LE period	Corrosion damage	Cracking due to corrosion effects	Regular Inspection	Minor damage in one region	Complete Structural Colapse	Asset sinking or capsizing	1	5	5
4.3.d	Starboard Ballast Tank Stiffener	To sustain the loads in the FPSO and hold ballast water	Further inspection is needed and possible replacement of stiffeners in 9.6 years.	Corrosion damage	Cracking due to corrosion effects	Regular Inspection	Minor damage in one region	Complete Structural Colapse	Asset sinking or capsizing	3	5	15
4.3.e	Port Cargo Tank Plate	To sustain the loads in the FPSO and hold oil	Further inspection is needed but no need for replacement during LE.	Corrosion damage	Cracking due to corrosion effects	Regular Inspection	Minor damage in one region	Complete Structural Colapse	Asset sinking or capsizing	1	5	5
4.3.f	Port Cargo Tank Stiffener	To sustain the loads in the FPSO and hold oil	Further inspection is needed but no need for replacement during LE.	Corrosion damage	Cracking due to corrosion effects	Regular Inspection	Minor damage in one region	Complete Structural Colapse	Asset sinking or capsizing	1	5	5
4.3.g	Starboard Cargo Tank Plate	To sustain the loads in the FPSO and hold oil	Further inspection is needed but no need for replacement during LE.	Corrosion damage	Cracking due to corrosion effects	Regular Inspection	Minor damage in one region	Complete Structural Colapse	Asset sinking or capsizing	1	5	5
4.3.h	Starboard Cargo Tank Stiffener	To sustain the loads in the FPSO and hold oil	Further inspection is needed but no need for replacement during LE.	Corrosion damage	Cracking due to corrosion effects	Regular Inspection	Minor damage in one region	Complete Structural Colapse	Asset sinking or capsizing	1	5	5
4.3.i	Center Cargo Tank Plate	To sustain the loads in the FPSO and hold oil	Further inspection is needed but no need for replacement during LE.	Corrosion damage	Cracking due to corrosion effects	Regular Inspection	Minor damage in one region	Complete Structural Colapse	Asset sinking or capsizing	1	5	5
4.3.j	Center Cargo Tank Stiffener	To sustain the loads in the FPSO and hold oil	Further inspection is needed but no need for replacement during LE.	Corrosion damage	Cracking due to corrosion effects	Regular Inspection	Minor damage in one region	Complete Structural Colapse	Asset sinking or capsizing	1	5	5

Figure C.9: Structural System Risk Analysis P2.

System		Functionality Description		Risk Ranking			Risk Mitigation				
REF	System/Subsystem /Element	Function	Life Extension Assessment Outcome	L	S	R	Mitigation Action	LM	SM	MR	RR
1	Accomodation Block										
1.3.a	External Accomodation Walls	The external region that sustain all the components of the accomodation block	In bad condition, will require a full painting of the area	3	5	15	Perform the necessary refurbishments and apply coating in the external walls	1	5	5	0.67
1.3.b	External Accomodation Walls	The external region that sustain all the components of the accomodation block	In bad condition, will require a full painting of the area	3	3	9	Perform the necessary refurbishments and apply coating in the external walls	1	5	5	0.44
1.4	Internal Accomodation Walls	Internal walls dividing the accomodation regions	Good condition, needs a few renewal and upgrades								
1.5.a	Process Deck Level Plate	The 'floor' section where the accomodation is located in the external main deck area	Average condition, needs more inspection and possible upgrades duuring LE period	2	5	10	Perform the necessary refurbishments and reinforcements	1	5	5	0.50
1.5.b	Process Deck Level Plate	The 'floor' section where the accomodation is located in the external main deck area	Average condition, needs more inspection and possible upgrades duuring LE period	2	3	6	Perform the necessary refurbishments and reinforcements	1	3	3	0.50
4	Midship Section										
4.1	Port Side Shell	To sustain the loads in the FPSO and hold ballast water	Average condition, needs more inspection and possible upgrades duuring LE period	3	5	15	Reinforce or replace as necessary	1	5	5	0.67
4.1.a	Ballast Tanks Plates	To sustain the loads in the FPSO and hold ballast water	First plate to need replacement in 8.9 years	3	5	15	Reinforce or replace as necessary	1	5	5	0.67
4.1.b	Ballast Tanks Stiffeners	To sustain the loads in the FPSO and hold ballast water	First stiffeners to need replacement in 7.6 years	3	5	15	Reinforce or replace as necessary	1	5	5	0.67
4.2	Starboard Side Shell	To sustain the loads in the FPSO and hold ballast water	Average condition, needs more inspection and possible upgrades duuring LE period	3	5	15	Reinforce or replace as necessary	1	5	5	0.67
4.2.a	Ballast Tanks Plates	To sustain the loads in the FPSO and hold ballast water	First plate to need replacement in 8.9 years	3	5	15	Reinforce or replace as necessary	1	5	5	0.67
4.2.b	Ballast Tanks Stiffeners	To sustain the loads in the FPSO and hold ballast water	First stiffeners to need replacement in 7.6 years	3	5	15	Reinforce or replace as necessary	1	5	5	0.67
4.3	Bottom Shell										
4.3.b	Port Ballast Tank Stiffener	To sustain the loads in the FPSO and hold ballast water	Further inspection is needed and possible replacement of stiffeners in 9.6 years.	3	5	15	Reinforce or replace as necessary	1	5	5	0.67
4.3.d	Starboard Ballast Tank Stiffener	To sustain the loads in the FPSO and hold ballast water	Further inspection is needed and possible replacement of stiffeners in 9.6 years.	3	5	15	Reinforce or replace as necessary	1	5	5	0.67

Figure C.10: Structural System Mitigation Actions.

C.2.4 Decision Making

System		Functionality Description	Decision Making		
REF	System/Subsystem/Element	Life Extension Assessment Outcome	Work (Action)	Compliance	Decision
1	Accomodation Block				
1.1.a	Windows	Good condition, will need some replacement during LE period	Fix winndows	Work not Required to attain Compliance	Perform work during Life Extension period as normal maintenance
1.1.b	Windows	Good condition, will need some replacement during LE period	Fix winndows	Work not Required to attain Compliance	Perform work during Life Extension period as normal maintenance
1.2	Inside Decks	Good condition, needs a few renewal and upgrades	Refurbish decks as needed	Work not Required to attain Compliance	Perform work during Life Extension period as normal maintenance
1.3.a	External Accomodation Walls	In bad condition, will require a full painting of the area	Perform the necessary refurbishments and apply coating in the external walls	Work Required to attain Compliance	Perform work before Life Extension Period during Yardstay/Drydock
1.3.b	External Accomodation Walls	In bad condition, will require a full painting of the area	Perform the necessary refurbishments and apply coating in the external walls	Work Required to attain Compliance	Perform work before Life Extension Period during Yardstay/Drydock
1.4	Internal Accomodation Walls	Good condition, needs a few renewal and upgrades	Perform the necessary work	Work Required to attain Compliance	Perform work before Life Extension Period during Yardstay/Drydock
1.5.a	Process Deck Level Plate	Average condition, needs more inspection and possible upgrades during LE period	Perform the necessary refurbishments and reinforcements	Work Required to attain Compliance	Perform work before Life Extension Period during Yardstay/Drydock
1.5.b	Process Deck Level Plate	Average condition, needs more inspection and possible upgrades during LE period	Perform the necessary refurbishments and reinforcements	Work Required to attain Compliance	Perform work before Life Extension Period during Yardstay/Drydock
2	Flare				
2.1	Flare Deck Support	Good condition, needs a few renewal and upgrades	Inspect to prove condition	Work Required to attain Compliance	Perform work before Life Extension Period during Yardstay/Drydock
3	Helideck				
3.1	Helideck Supports	Good condition, needs a few renewal and upgrades	Inspect to prove condition	Work Required to attain Compliance	Perform work before Life Extension Period during Yardstay/Drydock
3.2	Helideck Deck	Good condition, needs a few renewal and upgrades	Inspect to prove condition	Work Required to attain Compliance	Perform work before Life Extension Period during Yardstay/Drydock
4	Midship Section				
4.1	Port Side Shell				
4.1.a	Ballast Tanks Plates	First plate already needs replacement (1 year behind schedule) and next to be needed in 4 year of life extension period	Reinforce or replace as necessary	Work Required to attain Compliance	Perform work before Life Extension Period during Yardstay/Drydock
4.1.b	Ballast Tanks Stiffeners	First stiffeners to need replacement in 1 year during life extension period	Reinforce or replace as necessary	Work Required to attain Compliance	Perform work before Life Extension Period during Yardstay/Drydock
4.2	Starboard Side Shell				
4.2.a	Ballast Tanks Plates	First plate already needs replacement (1 year behind schedule) and next to be needed in 4 year of life extension period	Reinforce or replace as necessary	Work Required to attain Compliance	Perform work before Life Extension Period during Yardstay/Drydock
4.2.b	Ballast Tanks Stiffeners	First stiffeners to need replacement in 1 year during life extension period	Reinforce or replace as necessary	Work Required to attain Compliance	Perform work before Life Extension Period during Yardstay/Drydock
4.3	Bottom Shell				
4.3.a	Port Ballast Tank Plate	Further inspection is needed but first analysis does not show plate needing replacement during LE period	Inspect to prove condition	Work Required to attain Compliance	Perform work during Life Extension period as normal maintenance
4.3.b	Port Ballast Tank Stiffener	Further inspection is needed but first analysis does not show plate needing replacement during LE period	Inspect to prove condition	Work Required to attain Compliance	Perform work before Life Extension Period during Yardstay/Drydock
4.3.c	Starboard Ballast Tank Plate	Further inspection is needed but first analysis does not show plate needing replacement during LE period	Inspect more frequently to control possible effects	Work Required to attain Compliance	Perform work during Life Extension period as normal maintenance
4.3.d	Starboard Ballast Tank Stiffener	Further inspection is needed but first analysis does not show plate needing replacement during LE period	Inspect to prove condition	Work Required to attain Compliance	Perform work before Life Extension Period during Yardstay/Drydock
4.3.e	Port Cargo Tank Plate	Further inspection is needed but first analysis does not show plate needing replacement during LE period	Inspect to prove condition	Work Required to attain Compliance	Perform work before Life Extension Period during Yardstay/Drydock
4.3.f	Port Cargo Tank Stiffener	Further inspection is needed but first analysis does not show plate needing replacement during LE period	Inspect to prove condition	Work Required to attain Compliance	Perform work before Life Extension Period during Yardstay/Drydock
4.3.g	Starboard Cargo Tank Plate	Further inspection is needed but first analysis does not show plate needing replacement during LE period	Inspect to prove condition	Work Required to attain Compliance	Perform work before Life Extension Period during Yardstay/Drydock
4.3.h	Starboard Cargo Tank Stiffener	Further inspection is needed but first analysis does not show plate needing replacement during LE period	Inspect to prove condition	Work Required to attain Compliance	Perform work before Life Extension Period during Yardstay/Drydock
4.3.i	Center Cargo Tank Plate	Further inspection is needed but first analysis does not show plate needing replacement during LE period	Inspect to prove condition	Work Required to attain Compliance	Perform work before Life Extension Period during Yardstay/Drydock
4.3.j	Center Cargo Tank Stiffener	Further inspection is needed but first analysis does not show plate needing replacement during LE period	Inspect to prove condition	Work Required to attain Compliance	Perform work before Life Extension Period during Yardstay/Drydock

Figure C.11: Structural System Decision Making.

C.3 Firefighting System Analysis

C.3.1 Risk Analysis and Risk Mitigation

System		Functionality Description		Failure Description			Failure Effects			Risk		
REF	**System/Subsystem/Element**	**Function**	**Life Extension Assessment Outcome**	**Failure Cause or Mechanism**	**Failure Mode**	**Detection of Failure**	**Local Effects**	**Global Effect**	**Consequences**	**L**	**S**	**R**
1	Deluge and Distribution System											
1.1	Accom.											
1.1.a	APG 1	To transport fresh water into the specific location	Good condition - Pipe has just been replaced and RUL=11 years, i.e. longer than LE period	Corrosion	Corroded pipe can break down	Inspection with non-destructive methods	One section of the pipe breakdowns and stops working	Fire not coantained in accommodation block	Fire in the accommodation block	1	5	5
1.1.b	APG 2	To transport fresh water into the specific location	Good condition - Pipe has just been replaced and RUL=11 years, i.e. longer than LE period	Corrosion	Corroded pipe can break down	Inspection with non-destructive methods	One section of the pipe breakdowns and stops working	Fire not coantained in accommodation block	Fire in the accommodation block	1	5	5
1.1.c	APG 3	To transport fresh water into the specific location	Good condition - Pipe has just been replaced and RUL=11 years, i.e. longer than LE period	Corrosion	Corroded pipe can break down	Inspection with non-destructive methods	One section of the pipe breakdowns and stops working	Fire not coantained in accommodation block	Fire in the accommodation block	1	5	5
1.2	Machinery Room											
1.2.a	MRPG 1	To transport fresh water into the specific location	Good condition - Pipe has just been replaced and RUL=11 years, i.e. longer than LE period	Corrosion	Corroded pipe can break down	Inspection with non-destructive methods	One section of the pipe breakdowns and stops working	Fire not contained in machinery area	Fire in machinery room	1	4	4
1.2.b	MRPG 2	To transport fresh water into the specific location	Good condition - Pipe has just been replaced and RUL=11 years, i.e. longer than LE period	Corrosion	Corroded pipe can break down	Inspection with non-destructive methods	One section of the pipe breakdowns and stops working	Fire not contained in machinery area	Fire in machinery room	1	4	4
1.2.c	MRPG 3	To transport fresh water into the specific location	Good condition - Pipe has just been replaced and RUL=11 years, i.e. longer than LE period	Corrosion	Corroded pipe can break down	Inspection with non-destructive methods	One section of the pipe breakdowns and stops working	Fire not contained in machinery area	Fire in machinery room	1	4	4
1.2.d	MRPG 4	To transport fresh water into the specific location	Good condition - Pipe has just been replaced and RUL=11 years, i.e. longer than LE period	Corrosion	Corroded pipe can break down	Inspection with non-destructive methods	One section of the pipe breakdowns and stops working	Fire not contained in machinery area	Fire in machinery room	1	4	4
1.3	Control System											
1.3.a	CRP G1	To transport fresh water into the specific location	Good condition - Pipe has just been replaced and RUL=11 years, i.e. longer than LE period	Corrosion	Corroded pipe can break down	Inspection with non-destructive methods	One section of the pipe breakdowns and stops working	Fire not contained in control room	Loosing control of control systems	1	4	4
1.3.b	CRP G2	To transport fresh water into the specific location	Good condition - Pipe has just been replaced and RUL=11 years, i.e. longer than LE period	Corrosion	Corroded pipe can break down	Inspection with non-destructive methods	One section of the pipe breakdowns and stops working	Fire not contained in control room	Loosing control of control systems	1	4	4
2	Fire Water Pump Container											
2.1	Pump	To pump freshwater into the firefighting pipes	This pump has an average and has barely been used. Although it is maintained, the real condition is unknown.	Lack of maintenance	Components can be worn out if not properly maintained or substituted	Regular Inspection	Pump not working	Pump does not provide fluid to one region in the unit	Fire not contained	3	5	15
2.2	Diesel Engine	To power the fire water pumps	In general good condition, overhaul if needed	Lack of maintenance	Components can be worn out if not properly maintained or substituted	Regular Inspection	Equipment fails to provide power to firefighting system	No power in case of fire	Firefighting systems cannot be initiatied	1	4	4
2.3	Generator	To power the fire water pumps	In general good condition, overhaul if needed	Lack of maintenance	Components can be worn out if not properly maintained or substituted	Regular Inspection	Equipment fails to provide power to firefighting system	No power in case of fire	Firefighting systems cannot be initiatied	1	4	4
2.4	HVAC	To ventilate the firewater system	In general good condition, overhaul if needed	Lack of maintenance	HVAC system can breakdown if not properly maintained or replaced	Regular Inspection	Some regions with poor ventilation system	Toxic air in the region	Toxic air spreading to different areas of the FPSO putting life in danger	1	5	5
3	Surge Damping Tank	To hold fluid	In general good condition, just maintain as required	Corrosion	Corroded tank can break down	Regular Inspection	Sections of the tank can break down	Possible fluid leakage	No fluid to fight the fire	1	3	3
4	Air Evacuation System	To ventilate the firewater system	In general good condition, just maintain as required	Lack of maintenance	HVAC system can breakdown if not properly maintained or replaced	Regular Inspection	Some regions with poor ventilation system	Toxic air in the region	Toxic air spreading to different areas of the FPSO putting life in danger	1	4	4
5	Sprinkles	To flow water into fire region	In general good condition, just maintain as required	Lack of maintenance /replacement	Components not working properly	Regular Inspection	Some of the sprinkles might not be working	No firewater flowing	Fire spreading to other areas of the FPSO	1	5	5
6	Valves	To allow/close water passage	Around 10 valves of the entire system are in really bad condition	Time Deterioration and Lack of Replacemment	Components not working properly	Regular Inspection	Valves not opening/closing in one pipe section	Fluid not flowing or flowing too much into a specific region	Fire not contained	3	4	12

Figure C.12: Full Risk Analysis - Firefighting System.

C.4 Offloading System Analysis

C.4.1 Risk Analysis and Risk Mitigation

System		Functionality Description		Failure Description			Failure Effects			Risk Ranking		
REF	**System/Subsystem /Element**	**Function**	**Life Extension Assessment Outcome**	**Failure Cause or Mechanism**	**Failure Mode**	**Detection of Failure**	**Local Effects**	**Global Effect**	**Consequences**	**L**	**S**	**R**
1	Offloading Hoose											
1.1	DC-H Type Yokahoma	To transport the produced oil into the shuttle tanker	The hose condition is bad because it is old, hence should be substituted.	Age deteoration	Colapse or break down due to detereoation	Inspection ?	Offloading process has to be postponed/cancelled	Leakage of oil	Pollution to the ocean with cargo oil	4	5	20
2	Cargo Tanks											
2.1	Port Cargo Tanks	To hold the produced oil	Corrosion Allowance has already been consumed, and steel renewal work is expected during the life extension period. Deck plates are already under the thickness reduction limit for renewal work	Steel Corrosion	Cracking of steel plates or stiffeners	Regular Inspection	Cracking and opening in the tank	Oi Spilling into Ballast Tanks	Heeling of the vessel	3	5	15
2.1.1	PCT 1	To hold the produced oil	Corrosion Allowance has already been consumed, and steel renewal work is expected during the life extension period. Deck plates are already under the thickness reduction limit for renewal work	Steel Corrosion	Cracking of steel plates or stiffeners	Regular Inspection	Cracking and opening in the tank	Oi Spilling into Ballast Tanks	Heeling of the vessel	3	5	15
2.1.2	PCT 2	To hold the produced oil	Corrosion Allowance has already been consumed, and steel renewal work is expected during the life extension period. Deck plates are already under the thickness reduction limit for renewal work	Steel Corrosion	Cracking of steel plates or stiffeners	Regular Inspection	Cracking and opening in the tank	Oi Spilling into Ballast Tanks	Heeling of the vessel	3	5	15
2.1.3	PCT 3	To hold the produced oil	Corrosion Allowance has already been consumed, and steel renewal work is expected during the life extension period. Deck plates are already under the thickness reduction limit for renewal work	Steel Corrosion	Cracking of steel plates or stiffeners	Regular Inspection	Cracking and opening in the tank	Oi Spilling into Ballast Tanks	Heeling of the vessel	3	5	15
2.1.4	PCT 4	To hold the produced oil	Corrosion Allowance has already been consumed, and steel renewal work is expected during the life extension period. Deck plates are already under the thickness reduction limit for renewal work	Steel Corrosion	Cracking of steel plates or stiffeners	Regular Inspection	Cracking and opening in the tank	Oi Spilling into Ballast Tanks	Heeling of the vessel	3	5	15
2.1.5	PCT 5	To hold the produced oil	Corrosion Allowance has already been consumed, and steel renewal work is expected during the life extension period. Deck plates are already under the thickness reduction limit for renewal work	Steel Corrosion	Cracking of steel plates or stiffeners	Regular Inspection	Cracking and opening in the tank	Oi Spilling into Ballast Tanks	Heeling of the vessel	3	5	15
2.1.6	PCT 6	To hold the produced oil	Corrosion Allowance has already been consumed, and steel renewal work is expected during the life extension period.	Steel Corrosion	Cracking of steel plates or stiffeners	Regular Inspection	Cracking and opening in the tank	Oi Spilling into Ballast Tanks	Heeling of the vessel	3	5	15
2.1.7	PCT 7	To hold the produced oil	Corrosion Allowance has already been consumed, and steel renewal work is expected during the life extension period. Deck plates are already under the thickness reduction limit for renewal work	Steel Corrosion	Cracking of steel plates or stiffeners	Regular Inspection	Cracking and opening in the tank	Oi Spilling into Ballast Tanks	Heeling of the vessel	3	5	15
2.2	Central Cargo Tanks	To hold the produced oil	Corrosion Allowance has already been consumed, and steel renewal work is expected during the life extension period. Deck plates are already under the thickness reduction limit for renewal work	Steel Corrosion	Cracking of steel plates or stiffeners	Regular Inspection	Cracking and opening in the tank	Oi Spilling into other Tanks	Heeling of the vessel	3	3	9
2.2.1	CCT 1	To hold the produced oil	Corrosion Allowance has already been consumed, and steel renewal work is expected during the life extension period. Deck plates are already under the thickness reduction limit for renewal work	Steel Corrosion	Cracking of steel plates or stiffeners	Regular Inspection	Cracking and opening in the tank	Oi Spilling into other Tanks	Heeling of the vessel	3	3	9
2.2.2	CCT 2	To hold the produced oil	Corrosion Allowance has already been consumed, and steel renewal work is expected during the life extension period. Deck plates are already under the thickness reduction limit for renewal work	Steel Corrosion	Cracking of steel plates or stiffeners	Regular Inspection	Cracking and opening in the tank	Oi Spilling into other Tanks	Heeling of the vessel	3	3	9
2.2.3	CCT 3	To hold the produced oil	Corrosion Allowance has already been consumed, and steel renewal work is expected during the life extension period. Deck plates are already under the thickness reduction limit for renewal work	Steel Corrosion	Cracking of steel plates or stiffeners	Regular Inspection	Cracking and opening in the tank	Oi Spilling into other Tanks	Heeling of the vessel	3	3	9
2.2.4	CCT 4	To hold the produced oil	Corrosion Allowance has already been consumed, and steel renewal work is expected during the life extension period. Deck plates are already under the thickness reduction limit for renewal work	Steel Corrosion	Cracking of steel plates or stiffeners	Regular Inspection	Cracking and opening in the tank	Oi Spilling into other Tanks	Heeling of the vessel	3	3	9
2.2.5	CCT 5	To hold the produced oil	Corrosion Allowance has already been consumed, and steel renewal work is expected during the life extension period. Deck plates are already under the thickness reduction limit for renewal work	Steel Corrosion	Cracking of steel plates or stiffeners	Regular Inspection	Cracking and opening in the tank	Oi Spilling into other Tanks	Heeling of the vessel	3	3	9
2.2.6	CCT 6	To hold the produced oil	Corrosion Allowance has already been consumed, and steel renewal work is expected during the life extension period. Deck plates are already under the thickness reduction limit for renewal work	Steel Corrosion	Cracking of steel plates or stiffeners	Regular Inspection	Cracking and opening in the tank	Oi Spilling into other Tanks	Heeling of the vessel	3	3	9

Figure C.13: Full Risk Analysis 1 - Offloading System.

System		Functionality Description		Failure Description			Failure Effects			Risk Ranking		
REF	**System/Subsystem /Element**	**Function**	**Life Extension Assessment Outcome**	**Failure Cause or Mechanism**	**Failure Mode**	**Detection of Failure**	**Local Effects**	**Global Effect**	**Consequences**	**L**	**S**	**R**
1	Offloading Hoose											
1.1	DC-H Type Yokahoma	To transport the produced oil into the shuttle tanker	The hose condition is bad because it is old, hence should be substituted.	Age deteoration	Colapse or break down due to detereoation	Inspection ?	Offloading process has to be postponed/cancelled	Leakage of oil	Pollution to the ocean with cargo oil	4	5	20
2	Cargo Tanks											
2.1	Port Cargo Tanks	To hold the produced oil	Corrosion Allowance has already been consumed, and steel renewal work is expected during the life extension period. Deck plates are already under the thickness reduction limit for renewal work	Steel Corrosion	Cracking of steel plates or stiffeners	Regular Inspection	Cracking and opening in the tank	Oi Spilling into Ballast Tanks	Heeling of the vessel	3	5	15
2.1.1	PCT 1	To hold the produced oil	Corrosion Allowance has already been consumed, and steel renewal work is expected during the life extension period. Deck plates are already under the thickness reduction limit for renewal work	Steel Corrosion	Cracking of steel plates or stiffeners	Regular Inspection	Cracking and opening in the tank	Oi Spilling into Ballast Tanks	Heeling of the vessel	3	5	15
2.1.2	PCT 2	To hold the produced oil	Corrosion Allowance has already been consumed, and steel renewal work is expected during the life extension period. Deck plates are already under the thickness reduction limit for renewal work	Steel Corrosion	Cracking of steel plates or stiffeners	Regular Inspection	Cracking and opening in the tank	Oi Spilling into Ballast Tanks	Heeling of the vessel	3	5	15
2.1.3	PCT 3	To hold the produced oil	Corrosion Allowance has already been consumed, and steel renewal work is expected during the life extension period. Deck plates are already under the thickness reduction limit for renewal work	Steel Corrosion	Cracking of steel plates or stiffeners	Regular Inspection	Cracking and opening in the tank	Oi Spilling into Ballast Tanks	Heeling of the vessel	3	5	15
2.1.4	PCT 4	To hold the produced oil	Corrosion Allowance has already been consumed, and steel renewal work is expected during the life extension period. Deck plates are already under the thickness reduction limit for renewal work	Steel Corrosion	Cracking of steel plates or stiffeners	Regular Inspection	Cracking and opening in the tank	Oi Spilling into Ballast Tanks	Heeling of the vessel	3	5	15
2.1.5	PCT 5	To hold the produced oil	Corrosion Allowance has already been consumed, and steel renewal work is expected during the life extension period. Deck plates are already under the thickness reduction limit for renewal work	Steel Corrosion	Cracking of steel plates or stiffeners	Regular Inspection	Cracking and opening in the tank	Oi Spilling into Ballast Tanks	Heeling of the vessel	3	5	15
2.1.6	PCT 6	To hold the produced oil	Corrosion Allowance has already been consumed, and steel renewal work is expected during the life extension period.	Steel Corrosion	Cracking of steel plates or stiffeners	Regular Inspection	Cracking and opening in the tank	Oi Spilling into Ballast Tanks	Heeling of the vessel	3	5	15
2.1.7	PCT 7	To hold the produced oil	Corrosion Allowance has already been consumed, and steel renewal work is expected during the life extension period. Deck plates are already under the thickness reduction limit for renewal work	Steel Corrosion	Cracking of steel plates or stiffeners	Regular Inspection	Cracking and opening in the tank	Oi Spilling into Ballast Tanks	Heeling of the vessel	3	5	15
2.2	Central Cargo Tanks	To hold the produced oil	Corrosion Allowance has already been consumed, and steel renewal work is expected during the life extension period. Deck plates are already under the thickness reduction limit for renewal work	Steel Corrosion	Cracking of steel plates or stiffeners	Regular Inspection	Cracking and opening in the tank	Oi Spilling into other Tanks	Heeling of the vessel	3	3	9
2.2.1	CCT 1	To hold the produced oil	Corrosion Allowance has already been consumed, and steel renewal work is expected during the life extension period. Deck plates are already under the thickness reduction limit for renewal work	Steel Corrosion	Cracking of steel plates or stiffeners	Regular Inspection	Cracking and opening in the tank	Oi Spilling into other Tanks	Heeling of the vessel	3	3	9
2.2.2	CCT 2	To hold the produced oil	Corrosion Allowance has already been consumed, and steel renewal work is expected during the life extension period. Deck plates are already under the thickness reduction limit for renewal work	Steel Corrosion	Cracking of steel plates or stiffeners	Regular Inspection	Cracking and opening in the tank	Oi Spilling into other Tanks	Heeling of the vessel	3	3	9
2.2.3	CCT 3	To hold the produced oil	Corrosion Allowance has already been consumed, and steel renewal work is expected during the life extension period. Deck plates are already under the thickness reduction limit for renewal work	Steel Corrosion	Cracking of steel plates or stiffeners	Regular Inspection	Cracking and opening in the tank	Oi Spilling into other Tanks	Heeling of the vessel	3	3	9
2.2.4	CCT 4	To hold the produced oil	Corrosion Allowance has already been consumed, and steel renewal work is expected during the life extension period. Deck plates are already under the thickness reduction limit for renewal work	Steel Corrosion	Cracking of steel plates or stiffeners	Regular Inspection	Cracking and opening in the tank	Oi Spilling into other Tanks	Heeling of the vessel	3	3	9
2.2.5	CCT 5	To hold the produced oil	Corrosion Allowance has already been consumed, and steel renewal work is expected during the life extension period. Deck plates are already under the thickness reduction limit for renewal work	Steel Corrosion	Cracking of steel plates or stiffeners	Regular Inspection	Cracking and opening in the tank	Oi Spilling into other Tanks	Heeling of the vessel	3	3	9
2.2.6	CCT 6	To hold the produced oil	Corrosion Allowance has already been consumed, and steel renewal work is expected during the life extension period. Deck plates are already under the thickness reduction limit for renewal work	Steel Corrosion	Cracking of steel plates or stiffeners	Regular Inspection	Cracking and opening in the tank	Oi Spilling into other Tanks	Heeling of the vessel	3	3	9

Figure C.14: Full Risk Analysis 2 - Offloading System.

C.5 Power Generation System

C.6 Quantitative Model - Engines and Generators

2* **Diesel Engine 1 Operation Assessment**	**Information**		**Overhaul**		**Replacements**	
	Overhaul Interval (Running Hours)	**Expected Life Time (Running Hours)**	**Overhauls Performed**	**Remaining Time for Next Overhaul**	**Replacements Performed**	**Remaining Hours for Next Replacement**
Big End Bearing	16000	36000	6	12136	2	8136
Cylinder Head	16000	60000	6	12136	1	20136
Cylinder Liner	16000	180000	6	12136	0	80136
Exhaust Valve	15000	15000	6	5136	6	5136
Injection Nozzles	8000	8000	12	4136	12	4136
Injection Pump (Twin Pump)	12000	24000	8	8136	4	20136
Injection Pump, Pilot	24000	24000	4	20136	4	20136
Inlet Valve	150000	24000	0	50136	4	20136
Main Bearing	24000	36000	4	20136	2	8136
Piston	24000	36000	4	20136	2	8136
Piston Rings	16000	16000	6	12136	6	12136

Table C.1: Diesel Engine 1 - Operation Assessment

2* **Diesel Engine 2 Operation Assessment**	**Information**		**Overhaul**		**Replacements**	
	Overhaul Interval (Running Hours)	**Expected Life Time (Running Hours)**	**Overhauls Performed**	**Remaining Time for Next Overhaul**	**Replacements Performed**	**Remaining Hours for Next Replacement**
Big End Bearing	16000	36000	6	5894.5	2	1894.5
Cylinder Head	16000	60000	6	5894.5	1	13894.5
Cylinder Liner	16000	180000	6	5894.5	0	73894.5
Exhaust Valve	15000	15000	7	13894.5	7	13894.5
Injection Nozzles	8000	8000	13	5894.5	13	5894.5
Injection Pump (Twin Pump)	12000	24000	8	1894.5	4	13894.5
Injection Pump, Pilot	24000	24000	4	13894.5	4	13894.5
Inlet Valve	150000	24000	0	43894.5	4	13894.5
Main Bearing	24000	36000	4	13894.5	2	1894.5
Piston	24000	36000	4	13894.5	2	1894.5
Piston Rings	16000	16000	6	5894.5	6	5894.5

Table C.2: Diesel Engine 2 - Operation Assessment

2* **Diesel Engine 3 Operation Assessment**	**Information**		**Overhaul**		**Replacements**	
	Overhaul Interval (Running Hours)	**Expected Life Time (Running Hours)**	**Overhauls Performed**	**Remaining Time for Next Overhaul**	**Replacements Performed**	**Remaining Hours for Next Replacement**
Big End Bearing	16000	36000	6	10887.7	2	6887.7
Cylinder Head	16000	60000	6	10887.7	1	18887.7
Cylinder Liner	16000	180000	6	10887.7	0	78887.7
Exhaust Valve	15000	15000	6	3887.7	6	3887.7
Injection Nozzles	8000	8000	12	2887.7	12	2887.7
Injection Pump (Twin Pump)	12000	24000	8	6887.7	4	18887.7
Injection Pump, Pilot	24000	24000	4	18887.7	4	18887.7
Inlet Valve	150000	24000	0	48887.7	4	18887.7
Main Bearing	24000	36000	4	18887.7	2	6887.7
Piston	24000	36000	4	18887.7	2	6887.7
Piston Rings	16000	16000	6	10887.7	6	10887.7

Table C.3: Diesel Engine 3 - Operation Assessment

2*Diesel Engine 4 Operation Assessment	Information		Overhaul		Replacements	
	Overhaul Interval (Running Hours)	**Expected Life Time (Running Hours)**	**Overhauls Performed**	**Remaining Time for Next Overhaul**	**Replacements Performed**	**Remaining Hours for Next Replacement**
Big End Bearing	16000	36000	7	13156.4	3	29156.4
Cylinder Head	16000	60000	7	13156.4	1	5156.4
Cylinder Liner	16000	180000	7	13156.4	0	65156.4
Exhaust Valve	15000	15000	7	5156.4	7	5156.4
Injection Nozzles	8000	8000	14	5156.4	14	5156.4
Injection Pump (Twin Pump)	12000	24000	9	5156.4	4	5156.4
Injection Pump, Pilot	24000	24000	4	5156.4	4	5156.4
Inlet Valve	150000	24000	0	35156.4	4	5156.4
Main Bearing	24000	36000	4	5156.4	3	29156.4
Piston	24000	36000	4	5156.4	3	29156.4
Piston Rings	16000	16000	7	13156.4	7	13156.4

Table C.4: Diesel Engine 4 - Operation Assessment

2*Diesel Engine 5 Operation Assessment	Information		Overhaul		Replacements	
	Overhaul Interval (Running Hours)	**Expected Life Time (Running Hours)**	**Overhauls Performed**	**Remaining Time for Next Overhaul**	**Replacements Performed**	**Remaining Hours for Next Replacement**
Big End Bearing	16000	36000	6	2149.6	3	34149.6
Cylinder Head	16000	60000	6	2149.6	1	10149.6
Cylinder Liner	16000	180000	6	2149.6	0	70149.6
Exhaust Valve	15000	15000	7	10149.6	7	10149.6
Injection Nozzles	8000	8000	13	2149.6	13	2149.6
Injection Pump (Twin Pump)	12000	24000	9	10149.6	4	10149.6
Injection Pump, Pilot	24000	24000	4	10149.6	4	10149.6
Inlet Valve	150000	24000	0	40149.6	4	10149.6
Main Bearing	24000	36000	4	10149.6	3	34149.6
Piston	24000	36000	4	10149.6	3	34149.6
Piston Rings	16000	16000	6	2149.6	6	2149.6

Table C.5: Diesel Engine 5 - Operation Assessment

2*Diesel Engine 6 Operation Assessment	Information		Overhaul		Replacements	
	Overhaul Interval (Running Hours)	**Expected Life Time (Running Hours)**	**Overhauls Performed**	**Remaining Time for Next Overhaul**	**Replacements Performed**	**Remaining Hours for Next Replacement**
Big End Bearing	16000	36000	7	14404.7	3	30404.7
Cylinder Head	16000	60000	7	14404.7	1	6404.7
Cylinder Liner	16000	180000	7	14404.7	0	66404.7
Exhaust Valve	15000	15000	7	6404.7	7	6404.7
Injection Nozzles	8000	8000	14	6404.7	14	6404.7
Injection Pump (Twin Pump)	12000	24000	9	6404.7	4	6404.7
Injection Pump, Pilot	24000	24000	4	6404.7	4	6404.7
Inlet Valve	150000	24000	0	36404.7	4	6404.7
Main Bearing	24000	36000	4	6404.7	3	30404.7
Piston	24000	36000	4	6404.7	3	30404.7
Piston Rings	16000	16000	7	14404.7	7	14404.7

Table C.6: Diesel Engine 6 - Operation Assessment

2*Diesel Engine 8 Operation Assessment	Information		Overhaul		Replacements	
	Overhaul Interval (Running Hours)	**Expected Life Time (Running Hours)**	**Overhauls Performed**	**Remaining Time for Next Overhaul**	**Replacements Performed**	**Remaining Hours for Next Replacement**
Big End Bearing	16000	36000	2	15544.2	0.00	3544.2
Cylinder Head	16000	60000	2	15544.2	0.00	27544.2
Cylinder Liner	16000	180000	2	15544.2	0.00	147544.2
Exhaust Valve	15000	15000	2	12544.2	2.00	12544.2
Injection Nozzles	8000	8000	4	7544.2	4.00	7544.2
Injection Pump (Twin Pump)	12000	24000	2	3544.2	1.00	15544.2
Injection Pump, Pilot	24000	24000	1	15544.2	1.00	15544.2
Inlet Valve	150000	24000	0	117544.2	1.00	15544.2
Main Bearing	24000	36000	1	15544.2	0.00	3544.2
Piston	24000	36000	1	15544.2	0.00	3544.2
Piston Rings	16000	16000	2	15544.2	2.00	15544.2

Table C.8: Diesel Engine 8 - Operation Assessment

2*Diesel Engine 7 Operation Assessment	Information		Overhaul		Replacements	
	Overhaul Interval (Running Hours)	**Expected Life Time (Running Hours)**	**Overhauls Performed**	**Remaining Time for Next Overhaul**	**Replacements Performed**	**Remaining Hours for Next Replacement**
Big End Bearing	16000	36000	1	5785.7	0	9785.7
Cylinder Head	16000	60000	1	5785.7	0	33785.7
Cylinder Liner	16000	180000	1	5785.7	0	153785.7
Exhaust Valve	15000	15000	1	3785.7	1	3785.7
Injection Nozzles	8000	8000	3	5785.7	3	5785.7
Injection Pump (Twin Pump)	12000	24000	2	9785.7	1	21785.7
Injection Pump, Pilot	24000	24000	1	21785.7	1	21785.7
Inlet Valve	150000	24000	0	123785.7	1	21785.7
Main Bearing	24000	36000	1	21785.7	0	9785.7
Piston	24000	36000	1	21785.7	0	9785.7
Piston Rings	16000	16000	1	5785.7	1	5785.7

Table C.7: Diesel Engine 7 - Operation Assessment

C.7 Electronic System Analysis

C.7.1 Electronic Systems Overall Condition

				AS IS Condition'					
ID	System	Overall System Condition	Design Life	Refurbishments	Degree of Refurbishments	Replacements	Degree of Replacements	Failure and Incident	Maintenance
the elect	Engines, Engine Room and Automation								
1	Automation System, K-Chief								
1.1	Alarm and Monitoring System	Obsolete						Low	Maintained according to Software
1.2	Auxiliary Control System	Obsolete						Low	Maintained according to Software
1.3	Power Management System	Obsolete						Low	Maintained according to Software
1.4	Propulsion Control	Obsolete						Low	Maintained according to Software
1.5	Ballast System	Obsolete						Low	Maintained according to Software
1.6	Cargo Monitoring and Control	Obsolete						Low	Maintained according to Software
1.7	HVAC	Obsolete						Low	Maintained according to Software
2	Safety Management and Control System - K-Safe SMCS								
2.1	CCTV	Upgrades Required		Yes	Moderate	No		Low	Maintained according to Software
2.2	Safety Desk	Upgrades Required		Yes	Moderate	No		Low	Maintained according to Software
2.3	Plan Viewer	Upgrades Required		Yes	Moderate	No		Low	Maintained according to Software
2.4	Watertight Door	Upgrades Required		Yes	Moderate	No		Low	Maintained according to Software
2.5	Shell Door	Upgrades Required		Yes	Moderate	No		Low	Maintained according to Software
2.6	Low Location Light	Upgrades Required		Yes	Moderate	No		Low	Maintained according to Software
2.7	VDR	Upgrades Required		Yes	Moderate	No		Low	Maintained according to Software
2.8	Loading System	Upgrades Required		Yes	Moderate	No		Low	Maintained according to Software
2.9	Information Management System (IMS)	Upgrades Required		Yes	Moderate	No		Low	Maintained according to Software
3	Electrical Power Systems								
3.1	Energy Management System	Upgrades Required		Yes	Moderate	No		Low	Maintained according to Software
3.2	Power Management System	Upgrades Required		Yes	Moderate	No		Low	Maintained according to Software
3.3	Sensors and Machinery Monitoring	Upgrades Required		Yes	Moderate	No		Low	Maintained according to Software
Not repl	Engine Monitoring System								
4.1	Temperature Sensors, Signal Converters and Zener Barriers	Upgrades Required		Yes	Moderate	No		Low	Maintained according to Software
4.2	Marine Pressure Transmitters	Upgrades Required		Yes	Moderate	No		Low	Maintained according to Software
4.3	Marine Level Switches	Upgrades Required		Yes	Moderate	No		Low	Maintained according to Software
4.4	Bearing Wear Montoring System	Upgrades Required		Yes	Moderate	No		Low	Maintained according to Software
4.5	Water Ingress Detection System	Upgrades Required		Yes	Moderate	No		Low	Maintained according to Software
4.6	Tank Overflow/Overfill Protection System	Upgrades Required		Yes	Moderate	No		Low	Maintained according to Software
	Brigde								
5	Navigation System								
5.1	Gyro Compass System	Upgrades Required		Yes	Moderate	No		Low	Maintained according to Software
5.2	Position System	Upgrades Required		Yes	Moderate	No		Low	Maintained according to Software
5.3	Motion and Heading Sensors	Upgrades Required		Yes	Moderate	No		Low	Maintained according to Software
5.4	ARPA Radar	Upgrades Required		Yes	Moderate	No		Low	Maintained according to Software
5.5	AIS	Upgrades Required		Yes	Moderate	No		Low	Maintained according to Software
5.6	Autopilot	Upgrades Required		Yes	Moderate	No		Low	Maintained according to Software
5.7	Bridge Navigation Watch and Alert System	Upgrades Required		Yes	Moderate	No		Low	Maintained according to Software
5.8	Conning Display	Upgrades Required		Yes	Moderate	No		Low	Maintained according to Software
5.9	ECDIS (Electronic Chart Display)	Upgrades Required		Yes	Moderate	No		Low	Maintained according to Software
5.10	Navigation Sensor Integrator	Upgrades Required		Yes	Moderate	No		Low	Maintained according to Software
5.11	Stand Alone Voyage Data Recorder	Upgrades Required		Yes	Moderate	No		Low	Maintained according to Software
	Telecommunication System								
6	External Communication								
6.1	Transmission/Backbone	Upgrades Required		Yes	Moderate	No		Low	Maintained according to Software
6.2	Fibre Optic Communication	Upgrades Required		Yes	Moderate	No		Low	Maintained according to Software
6.3	Microwave Radio	Upgrades Required		Yes	Moderate	No		Low	Maintained according to Software
6.4	Marine Radio and GMDSS	Upgrades Required		Yes	Moderate	No		Low	Maintained according to Software
6.5	VSAT and INMARSAT	Upgrades Required		Yes	Moderate	No		Low	Maintained according to Software
6.6	SCADA Communication	Upgrades Required		Yes	Moderate	No		Low	Maintained according to Software
6.7	Offloading Telemetry	Upgrades Required		Yes	Moderate	No		Low	Maintained according to Software
6.8	Vessel Berthing System	Upgrades Required		Yes	Moderate	No		Low	Maintained according to Software
7	Internal Communication	Obsolete							
7.1	PABS and Telephone System	Upgrades Required		Yes	Moderate	No		Low	Maintained according to Software
7.2	UHF Tetra Tadio	Upgrades Required		Yes	Moderate	No		Low	Maintained according to Software
7.3	LAN/WAN and Structured Cabling System	Upgrades Required		Yes	Moderate	No		Low	Maintained according to Software
7.4	Wireless Distribution	Upgrades Required		Yes	Moderate	No		Low	Maintained according to Software
7.5	Paging System	Upgrades Required		Yes	Moderate	No		Low	Maintained according to Software
7.6	Drilleræ's Talkback	Upgrades Required		Yes	Moderate	No		Low	Maintained according to Software
7.7	Crane Radio	Upgrades Required		Yes	Moderate	No		Low	Maintained according to Software
7.8	Entertainment	Upgrades Required		Yes	Moderate	No		Low	Maintained according to Software
7.9	Video Conferencing	Upgrades Required		Yes	Moderate	No		Low	Maintained according to Software

Figure C.15: Electronic Systems - 'As Is' Condition.

	AS IS Condition'	Hardware Analysis					
ID	System	Condition Status Hardware	Support Availability Hardware	Spare Parts	Compliance with Rules and Regulations Hardware	Obsoleteness	Failure Rates Hardware
the elect	Engines, Engine Room and Automation						
1	Automation System, K-Chief						
1.1	Alarm and Monitoring System	Average	Moderate	Yes	Compliant - None to Low Efforts	Not Obsolete	Low
1.2	Auxiliary Control System	Average	Moderate	Yes	Compliant - None to Low Efforts	Not Obsolete	Low
1.3	Power Management System	Average	Moderate	Yes	Compliant - None to Low Efforts	Not Obsolete	Low
1.4	Propulsion Control	Average	Moderate	Yes	Compliant - None to Low Efforts	Not Obsolete	Low
1.5	Ballast System	Average	Moderate	Yes	Compliant - None to Low Efforts	Not Obsolete	Low
1.6	Cargo Monitoring and Control	Average	Moderate	Yes	Compliant - None to Low Efforts	Not Obsolete	Low
1.7	HVAC	Average	Moderate	Yes	Compliant - None to Low Efforts	Not Obsolete	Low
2	Safety Management and Control System - K-Safe SMCS						
2.1	CCTV	Average	Moderate	Yes	Compliant - None to Low Efforts	Not Obsolete	Low
2.2	Safety Desk	Average	Moderate	Yes	Compliant - None to Low Efforts	Not Obsolete	Low
2.3	Plan Viewer	Average	Moderate	Yes	Compliant - None to Low Efforts	Not Obsolete	Low
2.4	Watertight Door	Average	Moderate	Yes	Compliant - None to Low Efforts	Not Obsolete	Low
2.5	Shell Door	Average	Moderate	Yes	Compliant - None to Low Efforts	Not Obsolete	Low
2.6	Low Location Light	Average	Moderate	Yes	Compliant - None to Low Efforts	Not Obsolete	Low
2.7	VDR	Average	Moderate	Yes	Compliant - None to Low Efforts	Not Obsolete	Low
2.8	Loading System	Average	Moderate	Yes	Compliant - None to Low Efforts	Not Obsolete	Low
2.9	Information Management System (IMS)	Average	Moderate	Yes	Compliant - None to Low Efforts	Not Obsolete	Low
3	Electrical Power Systems						
3.1	Energy Management System	Obsolete	Not-Available	No	Not Compliant	Obsolete	Moderate
3.2	Power Management System	Obsolete	Not-Available	No	Not Compliant	Obsolete	Moderate
3.3	Sensors and Machinery Monitoring	Obsolete	Not-Available	No	Not Compliant	Obsolete	Moderate
Not repl	Engine Monitoring System						
4.1	Temperature Sensors, Signal Converters and Zener Barriers	Obsolete	Low	Yes	Compliant - High Efforts	Obsolete	Moderate
4.2	Marine Pressure Transmitters	Obsolete	Low	Yes	Compliant - High Efforts	Obsolete	Moderate
4.3	Marine Level Switches	Obsolete	Low	Yes	Compliant - High Efforts	Obsolete	Moderate
4.4	Bearing Wear Montoring System	Obsolete	Low	Yes	Compliant - High Efforts	Obsolete	Moderate
4.5	Water Ingress Detection System	Obsolete	Low	Yes	Compliant - High Efforts	Obsolete	Moderate
4.6	Tank Overflow/Overfill Protection System	Obsolete	Low	Yes	Compliant - High Efforts	Obsolete	Moderate
	Brigde						
5	Navigation System						
5.1	Gyro Compass System	Obsolete	Low	No	Compliant - High Efforts	Obsolete	Moderate
5.2	Position System	Obsolete	Low	No	Compliant - High Efforts	Obsolete	Low
5.3	Motion and Heading Sensors	Obsolete	Low	No	Compliant - High Efforts	Obsolete	Moderate
5.4	ARPA Radar	Obsolete	Low	No	Compliant - High Efforts	Obsolete	Moderate
5.5	AIS	Obsolete	Low	No	Compliant - High Efforts	Obsolete	Moderate
5.6	Autopilot	Obsolete	Low	No	Compliant - High Efforts	Obsolete	Moderate
5.7	Bridge Navigation Watch and Alert System	Obsolete	Low	No	Compliant - High Efforts	Obsolete	Moderate
5.8	Conning Display	Obsolete	Low	No	Compliant - High Efforts	Obsolete	Moderate
5.9	ECDIS (Electronic Chart Display)	Obsolete	Low	No	Compliant - High Efforts	Obsolete	Moderate
5.10	Navigation Sensor Integrator	Obsolete	Low	No	Compliant - High Efforts	Obsolete	Moderate
5.11	Stand Alone Voyage Data Recorder	Obsolete	Low	No	Compliant - High Efforts	Obsolete	Moderate
	Telecommunication System						
6	External Communication						
6.1	Transmission/Backbone	Obsolete	Low	No	Compliant - High Efforts	Obsolete	Moderate
6.2	Fibre Optic Communication	Obsolete	Low	No	Compliant - High Efforts	Obsolete	Moderate
6.3	Microwave Radio	Obsolete	Low	No	Compliant - High Efforts	Obsolete	Moderate
6.4	Marine Radio and GMDSS	Obsolete	Low	No	Compliant - High Efforts	Obsolete	Moderate
6.5	VSAT and INMARSAT	Obsolete	Low	No	Compliant - High Efforts	Obsolete	Moderate
6.6	SCADA Communication	Obsolete	Low	No	Compliant - High Efforts	Obsolete	Moderate
6.7	Offloading Telemetry	Obsolete	Low	No	Compliant - High Efforts	Obsolete	Moderate
6.8	Vessel Berthing System	Obsolete	Low	No	Compliant - High Efforts	Obsolete	Moderate
7	Internal Communication						
7.1	PABS and Telephone System	Obsolete	Low	No	Compliant - High Efforts	Obsolete	Moderate
7.2	UHF Tetra Tadio	Obsolete	Low	No	Compliant - High Efforts	Obsolete	Moderate
7.3	LAN/WAN and Structured Cabling System	Obsolete	Low	No	Compliant - High Efforts	Obsolete	Moderate
7.4	Wireless Distribution	Obsolete	Low	No	Compliant - High Efforts	Obsolete	Moderate
7.5	Paging System	Obsolete	Low	No	Compliant - High Efforts	Obsolete	Moderate
7.6	Drilleræ's Talkback	Obsolete	Low	No	Compliant - High Efforts	Obsolete	Moderate
7.7	Crane Radio	Obsolete	Low	No	Compliant - High Efforts	Obsolete	Moderate
7.8	Entertainment	Obsolete	Low	No	Compliant - High Efforts	Obsolete	Moderate
7.9	Video Conferencing	Obsolete	Low	No	Compliant - High Efforts	Obsolete	Moderate

Figure C.16: Electronic Systems - Hardware Condition.

	AS IS Condition'	Software Analysis								
ID	System	Condition Status	Failure Rates Software	Process/Data Analysis and Transfer Capability	Software Updates	Software Company	Support Availability Software	Human Competence	Compliance with Rules and Regulations Software	Complexity of Integration
the elect	Engines, Engine Room and Automation									
1	Automation System, K-Chief									
1.1	Alarm and Monitoring System	Average	Low	Moderate	Major	Major - Open	High	Available	Compliant - None to Low Efforts	High
1.2	Auxiliary Control System	Average	Low	Moderate	Major	Major - Open	High	Available	Compliant - None to Low Efforts	Moderate
1.3	Power Management System	Average	Low	Moderate	Major	Major - Open	High	Available	Compliant - None to Low Efforts	High
1.4	Propulsion Control	Average	Low	Moderate	Major	Major - Open	High	Available	Compliant - None to Low Efforts	Moderate
1.5	Ballast System	Average	Low	Moderate	Major	Major - Open	High	Available	Compliant - None to Low Efforts	Moderate
1.6	Cargo Monitoring and Control	Average	Low	Moderate	Major	Major - Open	High	Available	Compliant - None to Low Efforts	Moderate
1.7	HVAC	Average	Low	Moderate	Major	Major - Open	High	Available	Compliant - None to Low Efforts	Moderate
2	Safety Management and Control System - K-Safe SMCS									
2.1	CCTV	Average	Low	Moderate	Major	Major - Open	Moderate	Available	Compliant - None to Low Efforts	Low
2.2	Safety Desk	Average	Low	Moderate	Major	Major - Open	High	Available	Compliant - None to Low Efforts	High
2.3	Plan Viewer	Average	Low	Moderate	Major	Major - Open	Moderate	Available	Compliant - None to Low Efforts	Low
2.4	Watertight Door	Average	Low	Moderate	Major	Major - Open	Low	Available	Compliant - None to Low Efforts	Low
2.5	Shell Door	Average	Low	Moderate	Major	Major - Open	Low	Available	Compliant - None to Low Efforts	Low
2.6	Low Location Light	Average	Low	Moderate	Major	Major - Open	High	Available	Compliant - None to Low Efforts	Low
2.7	VDR	Average	Low	Moderate	Major	Major - Open	Moderate	Available	Compliant - None to Low Efforts	Low
2.8	Loading System	Average	Low	Moderate	Major	Major - Open	Moderate	Available	Compliant - None to Low Efforts	Low
2.9	Information Management System (IMS)	Average	Low	Moderate	Major	Major - Open	High	Available	Compliant - None to Low Efforts	High
3	Electrical Power Systems									
3.1	Energy Management System	Obsolete	Considerable	Moderate	Obsolete	Major - Open	Not-Available	Limited	Not Compliant	Moderate
3.2	Power Management System	Obsolete	Considerable	Moderate	Obsolete	Major - Open	Not-Available	Limited	Not Compliant	High
3.3	Sensors and Machinery Monitoring	Obsolete	Considerable	Moderate	Obsolete	Major - Open	Not-Available	Limited	Not Compliant	Moderate
Not repl	Engine Monitoring System									
4.1	Temperature Sensors, Signal Converters and Zener Barriers	Obsolete	Low	Moderate	Obsolete	Major - Open	Not-Available	Limited	Compliant - High Efforts	Low
4.2	Marine Pressure Transmitters	Obsolete	Low	Moderate	Obsolete	Major - Open	Low	Limited	Compliant - High Efforts	Low
4.3	Marine Level Switches	Obsolete	Low	Moderate	Obsolete	Major - Open	Not-Available	Limited	Compliant - High Efforts	Low
4.4	Bearing Wear Montoring System	Obsolete	Low	Moderate	Obsolete	Major - Open	Not-Available	Limited	Compliant - High Efforts	Low
4.5	Water Ingress Detection System	Obsolete	Low	Moderate	Obsolete	Major - Open	Low	Limited	Compliant - High Efforts	Low
4.6	Tank Overflow/Overfill Protection System	Obsolete	Low	Moderate	Obsolete	Major - Open	Low	Limited	Compliant - High Efforts	Low
	Brigde									
5	Navigation System									
5.1	Gyro Compass System	Obsolete	Low	Low	Obsolete	Major - Open	Low	Limited	Compliant - High Efforts	Low
5.2	Position System	Obsolete	Low	Low	Obsolete	Major - Open	Low	Limited	Compliant - High Efforts	Low
5.3	Motion and Heading Sensors	Obsolete	Low	Low	Obsolete	Major - Open	Low	Limited	Compliant - High Efforts	Low
5.4	ARPA Radar	Obsolete	Low	Low	Obsolete	Major - Open	Low	Limited	Compliant - High Efforts	Low
5.5	AIS	Obsolete	Low	Low	Obsolete	Major - Open	Low	Limited	Compliant - High Efforts	Low
5.6	Autopilot	Obsolete	Low	Low	Obsolete	Major - Open	Low	Limited	Compliant - High Efforts	Low
5.7	Bridge Navigation Watch and Alert System	Obsolete	Low	Low	Obsolete	Major - Open	Low	Limited	Compliant - High Efforts	Low
5.8	Conning Display	Obsolete	Low	Low	Obsolete	Major - Open	Low	Limited	Compliant - High Efforts	Low
5.9	ECDIS (Electronic Chart Display)	Obsolete	Low	Low	Obsolete	Major - Open	Low	Limited	Compliant - High Efforts	Low
5.10	Navigation Sensor Integrator	Obsolete	Low	Low	Obsolete	Major - Open	Low	Limited	Compliant - High Efforts	Low
5.11	Stand Alone Voyage Data Recorder	Obsolete	Low	Low	Obsolete	Major - Open	Low	Limited	Compliant - High Efforts	Low
	Telecommunication System									
6	External Communication									
6.1	Transmission/Backbone	Obsolete	Low	Moderate	Obsolete	Major - Open	Low	Limited	Compliant - High Efforts	Considerable
6.2	Fibre Optic Communication	Obsolete	Low	Moderate	Obsolete	Major - Open	Low	Limited	Compliant - High Efforts	Considerable
6.3	Microwave Radio	Obsolete	Low	Moderate	Obsolete	Major - Open	Low	Limited	Compliant - High Efforts	Considerable
6.4	Marine Radio and GMDSS	Obsolete	Low	Moderate	Obsolete	Major - Open	Low	Limited	Compliant - High Efforts	Considerable
6.5	VSAT and INMARSAT	Obsolete	Low	Moderate	Obsolete	Major - Open	Low	Limited	Compliant - High Efforts	Considerable
6.6	SCADA Communication	Obsolete	Low	Moderate	Obsolete	Major - Open	Low	Limited	Compliant - High Efforts	Considerable
6.7	Offloading Telemetry	Obsolete	Low	Moderate	Obsolete	Major - Open	Low	Limited	Compliant - High Efforts	Considerable
6.8	Vessel Berthing System	Obsolete	Low	Moderate	Obsolete	Major - Open	Low	Limited	Compliant - High Efforts	Considerable
7	Internal Communication									
7.1	PABS and Telephone System	Obsolete	Low	Moderate	Obsolete	Major - Open	Low	Limited	Compliant - High Efforts	Considerable
7.2	UHF Tetra Tadio	Obsolete	Low	Moderate	Obsolete	Major - Open	Low	Limited	Compliant - High Efforts	Considerable
7.3	LAN/WAN and Structured Cabling System	Obsolete	Low	Moderate	Obsolete	Major - Open	Low	Limited	Compliant - High Efforts	Considerable
7.4	Wireless Distribution	Obsolete	Low	Moderate	Obsolete	Major - Open	Low	Limited	Compliant - High Efforts	Considerable
7.5	Paging System	Obsolete	Low	Moderate	Obsolete	Major - Open	Low	Limited	Compliant - High Efforts	Considerable
7.6	Drilleræs Talkback	Obsolete	Low	Moderate	Obsolete	Major - Open	Low	Limited	Compliant - High Efforts	Considerable
7.7	Crane Radio	Obsolete	Low	Moderate	Obsolete	Major - Open	Low	Limited	Compliant - High Efforts	Considerable
7.8	Entertainment	Obsolete	Low	Moderate	Obsolete	Major - Open	Low	Limited	Compliant - High Efforts	Considerable
7.9	Video Conferencing	Obsolete	Low	Moderate	Obsolete	Major - Open	Low	Limited	Compliant - High Efforts	Considerable

Figure C.17: Electronic Systems - Software Condition.

C.8 Life Extension Work Packs

REF:	WP 1 - Steel Renewal		
Title:	Steel Renewal of Plates and Stiffeners		
Detail Level:	Feasibility		
Location:	During Yard Stay		
Estimated Time:	2385899.44		man-hours
Yard Rate:	10	USD/man-hours	$/man-hours
Estimated Cost:	$	23,858,994.38	
Total Weight (ton)	15065.81		
Comments:			

Background Information

Corrosion forecast models showed that the plates in ballast tanks and cargo tanks will be under acceptable criteria during the life extension period. Hence, it is recommended to do renewal steel work in the required regions. The model only considers the plate/stiffeners thinks, therefore in order to have a more accurate results while estimating the man-hours required for the work, a work factor has been inserted - These values should be replaced after inspection is performed in the unit and a better undertanding of which plates will be under the criteria is known.

Activity Description

Steel Renewal work to be performed the necessary locations - process deck, ballast tanks and cargo tanks

Cost Calculation

ID	System	A (m)	B (m)	t (mm)	Area (m2)	Vol (m3)	Density (kg/m3)	Weight (kg)	Weigth (ton)	Man-Hours per tonne	Correction for Location - External	Correction for Location - Internal	Corrected Man-Hours per Tonne	Quantity of Systems	Total Weigth (ton)	Work Factor	Colum n1	Total Man-Hours
1	Ballast Tanks - Plates - Side Shell 1	7.40	35.00	26.00	259.00	6.73	8000.00	53872.00	53.87	170	1.1	1.25	399.50	14	754.21	0.7	527.95	89750.75
2	Ballast Tanks - Plates - Side Shell 2	5.90	35.00	17.50	206.50	3.61	8000.00	28910.00	28.91	210	1.1	1.25	493.50	14	404.74	0.7	283.32	59496.78
3	Ballast Tanks - Plates - Side Shell 3	6.60	35.00	21.50	231.00	4.97	8000.00	39732.00	39.73	190	1.1	1.25	446.50	14	556.25	0.7	389.37	73980.98
4	Ballast Tanks - Plates - Side Shell 4	6.40	35.00	22.50	224.00	5.04	8000.00	40320.00	40.32	185	1.1	1.25	434.75	14	564.48	0.7	395.14	73100.16
5	Deck Plate (Whole Hull)	240.00	51.80	30.00	12432.00	372.96	8000.00	2983680.00	2983.68	150	1.15		172.50	10	29836.80	0.4	11935	1790208.00
6	Ballast/Cargo Tanks - Longitudinal 2	4.00	35.00	17.50	140.00	2.45	8000.00	19600.00	19.60	210		1.25	262.50	14	274.40	0.5	137.2	28812.00
7	Ballast/Cargo Tanks - Longitudinal 2	3.70	35.00	19.50	129.50	2.53	8000.00	20202.00	20.20	200		1.25	250.00	28	565.66	0.5	282.83	56565.60
8	Ballast/Cargo Tanks - Longitudinal 3	3.90	35.00	21.50	136.50	2.93	8000.00	23478.00	23.48	190		1.25	237.50	28	657.38	0.5	328.69	62451.48
9	Ballast/Cargo Tanks - Longitudinal 4	3.53	35.00	22.50	123.40	2.78	8000.00	22212.27	22.21	185		1.25	231.25	28	621.94	0.5	310.97	57529.79
10	Fuel Tank - Plates - 1	10.70	20.00	17.50	789.00	13.81	8000.00	110460.00	110.46	210			210.00	2	220.92	1	220.92	46393.20
11	Fuel Tank - Plates - 2	10.70	9.00	30.00	96.30	2.89	8000.00	23112.00	23.11	150			150.00	2	46.22	1	46.224	6933.60
12	Fuel Tank - Plates - 3	9.00	20.00	17.50	180.00	3.15	8000.00	25200.00	25.20	210			210.00	2	50.40	1	50.4	10584.00
13	Fuel Tank - Plates - 4	10.70	9.00	31.00	96.30	2.99	8000.00	23882.40	23.88	145			145.00	2	47.76	1	47.765	6925.90
14	Fuel Tank - Plates - 5	10.70	20.00	17.50	214.00	3.75	8000.00	29960.00	29.96	210			210.00	2	59.92	1	59.92	12583.20
15	Fuel Tank - Plates - 6	9.00	20.00	17.50	180.00	3.15	8000.00	25200.00	25.20	210			210.00	2	50.40	1	50.4	10584.00

Figure C.18: Work Pack 1.

REF:	WP 2 - Hull Painting
Title:	Painting of External Hull Areas
Detail Level:	Feasibility
Location	During Yard Stay
Total Area (m2)	29248.61
Yard Rate:	10 USD/m2
Estimated Cost:	$ 292,486.09
Comments:	

Background Information

After 15 years of operation it is interesting to repaint the external areas of the asset before entering the new life extension period. This work pack considers only the hull above design draft line, process deck and accommodation- The dimensions were imported from the 3D model of the unit.

Activity Description

Paint the external areas of the hull - hull external above design draft (includding green water protection), process deck and accommodation areas.

Cost Calculation

ID	System	A (m)	B (m)	t (mm)	Area (m2)
1	Hull External (Including Green Water Protection)	-	-	-	12655.64
2	Process Deck	-	-	-	14616.86
3	Accommodation	-	-	-	1976.11

Figure C.19: Work Pack 2.

REF:	WP 3 - Anodes Replacement	
Title:	Replacement of Anodes in Underwater Area of the Hull	
Detail Level:	Feasibility	
Location	During Yard Stay	
Underwater Area (m2)	17536.05	
Anodes Change Frequency (years)	5.00	
Capacity of Material (amp*hours/kg)	781.00	
Current Density of Material (mA/m2)	20.00	(Ave 10-30)
K	8760.00	
Cuurent (A)	350.72	
Total Weight Anodes (kg)	19669.12	
Anodes Weight (kg)	10.00	
Number of Anodes Required	1966.91	
Man-Hours for 10 kg	1.50	
Total Man-Hours	2950.37	
Yard Rate:	10.00	USD/man-hours
Estimated Cost:	$ 29,503.67	
Comments:	This work pack includes only the yard rate, and not material price	

Background Information

It is defined that the anodes in underwater hull area should be replaced before entering the life extension period - a replacement frequency of 5 years was selected.

Activity Description

Paint the external areas of the hull - hull external above design draft (includding green water protection), process deck and accommodation areas.

Figure C.20: Work Pack 3.

REF:	WP 4 - Firefighting Valves Replacements	
Title:	Replacement of Valves that are in bad condition from Firefighting Systems	
Detail Level:	Feasibility	
Location	During Yard Stay	
Underwater Area (m2)	17536.05	
Valve Bore (mm)	150.00	
Valve Type	Butterfly Valve	
Current Density of Material (mA/m2)	20.00	
Man-Hours per each Valve	11.50	
Total Number of Valves	20.00	
Total Man-Hours	230.00	
Yard Rate:	10.00	USD/man-hours
Estimated Cost:	$ 2,300.00	
Comments:	This work pack includes work in butterfly valves - remove, clean, checking, testing bedding of seal, paint internal exporsed areas and refit; excluding operating gear (Butler, 2020).	

Background Information

The firefighting system life extension assessment showed that some of the valves are in bad condition and require updates. Here, it is assumed that this refers to 20 butterfly type valves with 150 mm bore.

Activity Description

In situ overhaul - Butterfly Valve: remove, clean, checking, testing bedding of seal, paint internal exporsed areas and refit; excluding operating gear (Butler, 2020).

Figure C.21: Work Pack 4.

REF:	WP 5 - Offloading Hose Replacement
Title:	Replacement of Offloading Hose
Detail Level:	Feasibility
Location	During Yard Stay
Total Area (m2)	
Yard Rate:	USD/m2
Estimated Cost:	$ 200,000.00
Comments:	

Background Information

After 15 years of operation it is interesting to repaint the external areas of the asset before entering the new life extension period. This work pack considers only the hull above design draft line, process deck and accommodation- The dimensions were imported from the 3D model of the unit.

Activity Description

Paint the external areas of the hull - hull external above design draft (includding green water protection), process deck and accommodation areas.

Cost Calculation

ID	System	A (m)	B (m)	t (mm)	Area (m2)
1	Hull External (Including Green Water Protection)	-	-	-	12655.64
2	Process Deck	-	-	-	14616.86
3	Accommodation	-	-	-	1976.11

Figure C.22: Work Pack 5.

REF:	WP 6 - Overhaul Main Engine	
Title:	Overhual of Main Engines	
Detail Level:	Feasibility	
Location	During Yard Stay	
Cylinder Bore (mm)	460.00	
Stroke (mm)	580.00	
Number of Cylinders	16.00	
Piston Pins	16.00	
Inlet Valves	2.00	
Exhaust Valves	2.00	
Pump Capacity - Main (m3/h)	314.00	
Total Man-Hours per Engine	2962.90	
Number of Engines	6.00	
Total Man-Hours	17777.39	
Yard Rate:	10	USD/m2
Estimated Cost:	$ 177,773.87	
Comments:		

Background Information

After 15 years of operation it is interesting to repaint the external areas of the asset before entering the new life extension period. This work pack considers only the hull above design draft line, process deck and accommodation- The dimensions were imported from the 3D model of the unit.

Activity Description

Paint the external areas of the hull - hull external above design draft (includding green water protection), process deck and accommodation areas.

Cost Calculation

System	Overhaul before LE?	Man Hours per Component	Quantity of Components per Engine	Total Man Hours per Engine
Big End Bearing	NO			
Cylinder Head	YES	49.07	16.00	785.07
Cylinder Liner	YES	49.07	16.00	785.07
Cylinder	YES	57.24	16.00	915.91
Exhaust Valve	YES	11.50	32.00	368.00
Injection Nozzles	NO			
Injection Pump (Twin Pump)	YES	54.43	1.00	54.43
Injection Pump, Pilot	YES	54.43	1.00	54.43
Inlet Valve	NO		32.00	
Main Bearing	NO	18.40		
Piston	NO	15.33		
Piston Rings	YES	15.33		0.00

Figure C.23: Work Pack 6.

REF:	WP 7 - Overhaul of Pumps
Title:	Overhaul of firefighting and cargo pumps
Detail Level:	Feasibility
Location:	During Yard Stay
Estimated Man-Hours:	585.60
Yard Rate:	10 USD/man-hours
Estimated Cost:	$ 5,856.00
Comments:	This work packs does not consider any other type of pump, besides cargo and firewater pumps.

Background Information

The overhaul time for each pump is calculated based on assumptions of their capacity. For the firefighting system, a value of 600 m3/hours is selected and for the cargo pumps an average value for the pump's capacity range is selected. Also, it is considered that all the cargo pumps shall be overhauled

Activity Description

"Diconnecting and removing top half casing, releasing shaft coupling from motor drive, slinging and removing impeller, shaft and wearing ring. Withdraw impeller, shaft sleeve and bearings from shaft. Cleaning all exposed parts, calibrating and report. Reassembling as before using owner's supplied parts, jointing materials and fastenings" (Butler, 2012)

Cost Calculation

ID	System	Capacity (m3/hours)	Quantity	Man-hours per Pump	Total Man-Hours
1	Firefighting Pump	600.00	1.00	67.20	67.20
2	Cargo Pumps (Average Deliver Value)	1800.00	6.00	86.40	518.40

Figure C.24: Work Pack 7.

REF:	WP 8 - Tank Painting
Title:	Painting of Internal Areas in Ballast Tanks and required areas of Cargo Tanks
Detail Level:	Feasibility
Location	During Yard Stay
Total Area (m2)	55556.00
Yard Rate:	10 USD/m2
Estimated Cost:	$ 555,560.00
Comments:	

Background Information

After 15 years of operation it is interesting to repaint the external areas of the asset before entering the new life extension period. This work pack considers only the hull above design draft line, process deck and accommodation- The dimensions were imported from the 3D model of the unit.

Activity Description

Paint the external areas of the hull - hull external above design draft (includding green water protection), process deck and accommodation areas.

Cost Calculation

ID	System	A (m)	B (m)	t (mm)	Area (m2)
1	Ballast Tanks - Port	-	-	-	15539.80
2	Ballast Tanks - Starboard				15539.80
3	Cargo Tanks - Port	-	-	-	8074.80
4	Cargo Tanks - Center				8326.80
5	Cargo Tanks - Starboard				8074.80

Figure C.25: Work Pack 8.

Appendix D

Thesis Article

D.1 Thesis Article

This section presents an article developed based on the master thesis.

A CONDITION BASED, RISK ANALYSIS AND LIFE CYCLE ORIENTED APPROACH FOR LIFE EXTENSION OF FPSO UNITS

Amanda Caroline Rossi[1],
Supervisor: Odd Weisæth[S1], **and Supervisor: Henrique Gaspar**[S2]

[1]**amandacr@stud.ntnu.no**

ABSTRACT

This article proposes a methodology to assist in the decision-making process of whether a FPSO unit is suitable for life extension or not. The methodology proposed is divided in 7 stages. It starts with a general overview of the asset condition and then analysis each selected marine system condition individually. Quantitative and semi-quantitative models were created that can forecast time for replacement and overhaul. The quantitative and qualitative models are summarized and used as inputs to a risk analysis – what could happen to the unit is forecasted and risk as ranked according to a risk matrix. Whenever risks sit in the intolerable area they are mitigated, while some in the ALARP (As Low as Reasonable Practical) may be mitigated depending upon the assessment. The mitigation actions are used as input to the development of work packs. Then, CAPEX (Capital Expenditures) and OPEX (Operational Expenses) are calculated and a fesibility economical analysis is performed considering the shipowner and oil company business perspectives – a desired charter rate is find and used to established the minimum oil price for the project to be feasible.

Keywords: FPSO, Life Extension, Marine System, Decommissioning, Condition, Economical Feasibility Analysis, Life Cycle

INTRODUCTION

This paper main objective is to present a methodology developed a to assist in decision-making process of whether FPSO units are suitable for life extension or not. Life extension projects are responsible for assessing whether a unit is capable to operate for longer than initially anticipated at the same oil field.

As an FPSO is a gigantic structure with numerous systems, subsystems and equipment's, it is necessary to shorten the amount studied. It is common to have status at the equipment level, but for a fast and efficient approach, it is necessary to understand the condition of the systems. The methodology selected some specific systems for life extension and propose a procedure to gather the information on them.

How the systems can impact the asset performance and life extension scope of work is necessary to be known. Many different risks are associated with each system, hence it is necessary that the risks associated with life extension are understood and possibly mitigated .

The same system can have different risk categories, so it is important that a "general" risk picture is defined. Risk mitigation also influences the life extension strategy - one must understand what is the actual cost of doing something regarding a problem now, or if it is better to wait until upgrades start to be done.

Remaining useful life of equipment's has extensive literature available, and it is much more complex than simply calculating the design life of the equipment minus the time in operation. Maintenance and the system's current condition are the factors that drive most of the analysis considering remaining useful life. The methodology developed different quantitative and semi-quantitative models to predict useful life, time for component replacement and overhauls intervals .

The qualitative and quantitative information, as well as the risk analysis were used as input to develop work packs in order to fully describe and cost the work scope required to make the unit suitable for life extension. A detailed cost model was not performed, but it was possible to calculate CAPEX, OPEX and value for selling the vessel for scrap .

Lastly, an economical feasibility analysis is performed finding what would the minimum charter rate required for the shipowner to meet a set of required goals. This value is evaluated in the oil company side, and a minimum oil price for the life extension period was found. All the analysis were done for a mock-up FPSO .

METHODOLOGY DEVELOPMENT

The methodology created is divided into 7 phases, as presented in Figure 1. Although illustrated in a linear way, the process is interactive between the phases and the foundations (theoretical research and case study).

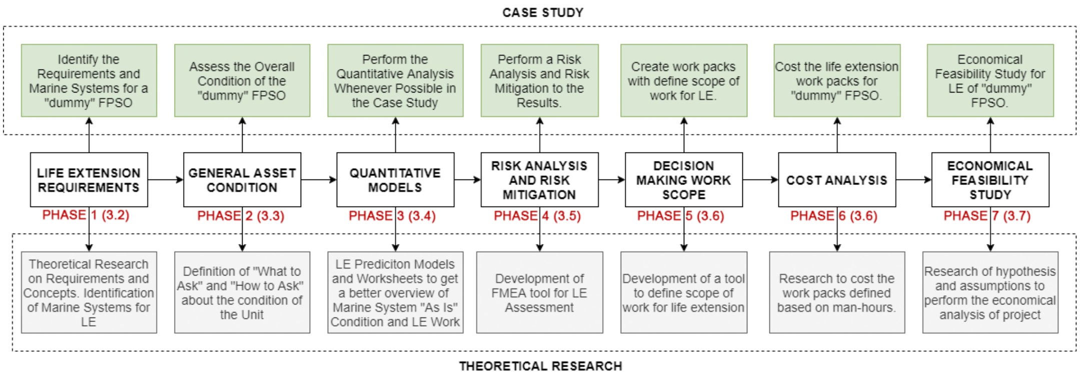


Figure 1. Diagram with Thesis Methodology.

The first stage on the methodology is defining what are the life extension requirements, hence understanding that a life extension project is part of the decommission phase in a FPSO life cycle. It stands for extending the operational life of the asset while keeping operation at the same oil field. This phase also defines the level of detail the thesis is subjected too, considering traditional concepts on engineering projects life cycle presented by Roseke (2015). This assessment is made for concept/feasibility level, hence meaning it deals with both qualitative and quantitative assessments.

Two economical concepts required in the methodology development are CAPEX (Capital Expenditures) and OPEX (Operational Expenses). The CAPEX represents all the cost required to extend the field and FPSO life, while OPEX gathers the day-to-day expenses to keep the unit running. Lastly, phase 1 finishes by defining what marine systems are to be analysed. This is due because a FPSO is a complex structure and it was no possible to assess all the systems onboard. For the case study, it was selected to analyse the structural system, firefighting system, offloading systems, power generation system and telecommunication systems.

Second phase in the methodology is analysing the general asset condition by the development of computational tool. Here, some questioning is done considering the general condition of the main systems - whether they've been maintained, what is the overall system condition, if there are spare parts required, if the system is being used and what is its usage status and more. With the condition know, what has to be done to extend the units life is forecasted and information regarding scope of work, type of work and scope location are required. The template allows for the development of dashboard that can present visually what is the current asset condition.

The methodology proceeds with the development of quantitative models. The systems selected in the phases before were organized into subsystems, and it was possible to group them into similar procedures. Four quantitative and qualitative models were created: structural components, pipes, rotating equipment and electronic systems.

"The structural components analyse how much time is left before the corrosion allowance is consumed and how long until the minimum thickness renewal criteria is reached. In principal, the thickness of the structure is governed by Equation 1, where t_{final} is the plate thickness after corrosion, t_0 is the initial thickness, i.e. the design or gross thickness thickness and $t_{corrosion}(t)$ is the corroded amount. This equation is defined as a function of time, because the longer the asset's exposure in a corrosive environment, the higher is its exposure to corrosion effects."'

$$t_{final}(t) = t_0 - t_{corrosion}(t) \tag{1}$$

'Also, coating is applied in marine structures so that the corrosion effects can be reduced. This should be taken into consideration when predicting how much useful time is left to the unit, as the coating layer has also a life time .

DNVGL-CG-0172: Thickness Diminution for Mobile Offshore Units proposes the use of a "Diminution Coefficient, k, to calculated what is the allowable thickness reduction before a renewal must be carried out in a structural member". The renewal thickness, t_{ren}, is calculated by Equation 2 and is the criteria to later calculate the remaining life. The key factor into the analysis is defining the annual corrosion rates for each member group. This can be done based on statistics analysis when it is available, or by regulations and experts opinion.

$$t_{ren} = k * t_{gross} \tag{2}$$

The remaining useful life, RUL, is calculated by forecasting how long the steel member lasts before reaching the renewal criteria. This is done by calculating a corrosion allowance and dividing by the corrosion rate, as presented in Equation 3.

$$RUL_{StructuralMembers} = \frac{t_{current} - t_{ren}}{C} \tag{3}$$

A parameter $t_{current}$ is included because in principal, remaining useful life is calculate to the 'As Is' condition of the unit. Therefore, the thickness values should be found in inspections reports. If the t_d is used, one is actually forecasting the design life of the structure, and not the remaining life.

The second quantitative model developed is destined to evaluate corrosion effects in piping systems, and the procedure is just as described in the structural components presented before. Then, the third quantitative models calculates time for component replacement and time between overhauls. Figure 2 gives an overview of how the analysis is done.

As input to the analysis, it is required to have the replacement and overhauls time frames from suppliers, and also to know how long the system has been operations. This tool allows for forecasting how many times a rotating equipment will require overhaul and then decide when to do it: before or after the life extension period.

Figure 2. Predicting RUL and Next Overhauling for a Component of a Diesel Engine .

The last model created are for the electronic systems, and here are included both the control and telecommunication systems. The analysis is similar to the general asset condition, but here it is analysed the system condition, hardware condition and software condition. A computational tool is created that assess different parameters, as presented in Figure 3.

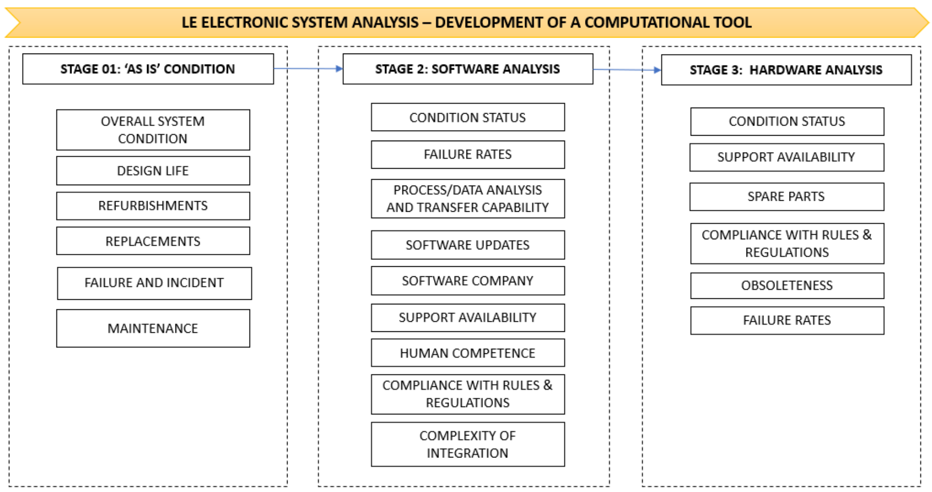


Figure 3. The Life Extension Analysis for Electronic Systems .

The methodology follows by performing a risk analysis and risk mitigation to each of the marine systems selected before. The risk analysis is performed based on a FMEA, and is summarized by Figure 4. The first stage into the procedure is gathering all the information obtained before to identify the system functionally and life extension out comes. Stage 2 is responsible for forecasting what would happen to the unit if the original condition is kept, and then the consequences are ranked. Whenever a risk sits in the intolerable area it has to be mitigated, while the ones the ALARP (As Low as Reasonable Practical) need to be investigated separately .

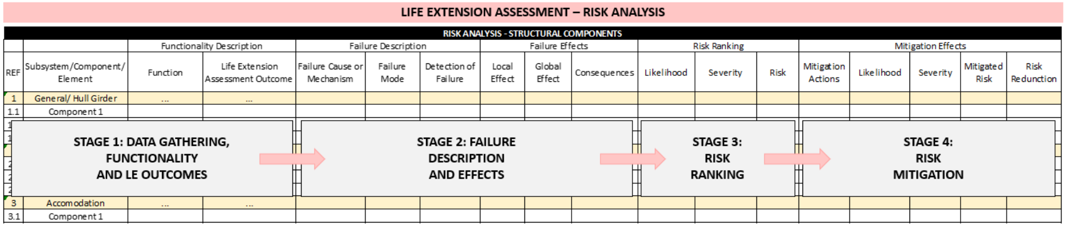


Figure 4. Overview of Risk Analysis and Risk Mitigation .

The mitigation actions are used as input to phases 5 and 6. Work packs are created considering what has to be done for the systems to achieve compliance, and then a simple cost analysis is performed to cost the work packs. Whenever possible, guidelines from the book "Ship Repair Estimates in man-hours" from Butler (2012).

The methodology finishes by performing a economical feasibility analysis. In this assessment, CAPEX and OPEX prices are calculated, and many assumptions are done considering profit margins and financing rates. The final result should be a parameter to be used in the decision-making process of whether a unit is suitable for life extension or not.

MOCK-UP FPSO BASED ON A REAL CASE SCENARIO

A FPSO is required in order to test out the methodology, therefore a mock-up version was created based on a real case scenario. The unit should operate in the Brazilian Continental Shelf, on a hypothetical oil field located at Santos Basin. With that known, a bench mark was done and a database was created with information from units operating in that region. The database created is based on information available at website MarineTraffic, shipowners and Ha et al. (2017).

Defining that the unit should store 1 MBBLS and process 170,000 bbl/day, it was possible to find the vessel main dimensions, which are presented in Table 1.

Storage Capacity	1000000	BBLS
Dimension Ratios		
L/B	6.03	
B/T	2.70	
B/D	1.98	
T/D	0.67	
FPSO Dimensions		
L	312.7	m
B	51.8	m
T	19.2	m
D	26.2	m
C_B	0.76	
∇	235712.3	m^3

Table 1. FPSO Dimensions and Ratios .

However, with the objective to test out the methodology, it was also required to define parameters for the marine systems selected for the analysis. Hence, a research was done in available literature and suppliers websites, but also many assumptions were required. Paik and Thayamballi (2007) presents the general arrangement and midiship sections selected, while suppliers like Wärtsilä (2019), Framo (2020), Eureka (2016), Yokahoma (2018) and Pipefit (2020) were used to select the remaining systems.

CASE STUDY: LIFE EXTENSION OF A MOCK-UP FPSO

The case study starts by defining what are the life extension requirements for the FPSO being anlysed and then follows by giving a general overview of the entire asset condition. The condition assessment is also done for each of the marine systems, as well as the risk analysis. When all the systems are analysed, the inputs are gathered into work packs that are later costed. CAPEX and OPEX prices are established, and a economical feasibility analysis is performed to determine what is the minimum oil price required for the project to be profitable - based on a minimum charter rate defined by a set of goals created for the mock-up life extension project.

For this assessment, the FPSO has been operating for 15 years and is being analysed to operate for 10 more years. Assuming that the design life is 20 years, this means that the FPSO will operate for 5 years above it. The idea on extending the unit life is connected to extending the field life, as seen in Figure 5 During the operational phase, another well was connected to the production what increase the field production profile and thus a life extension project is justifiable.

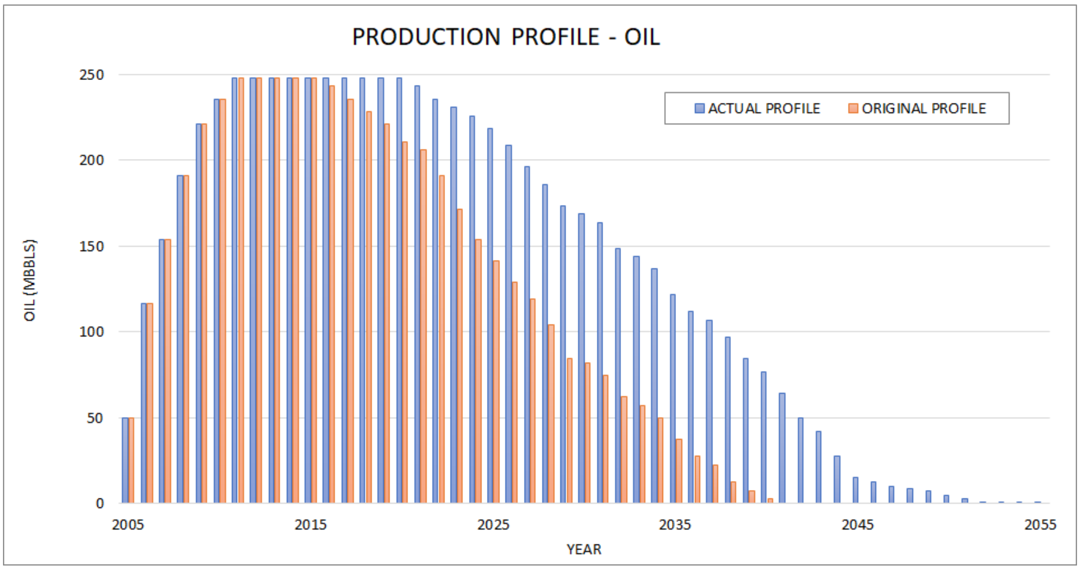


Figure 5. The Field Oil Production Profile .

To proceed with the case, different assumptions had to be made that included coating life in structural elements, power usage, maintenance condition and offloading frequency. The first phase in the methodology is the asset condition, hence an assessment was made considering the entire FPSO first, and then each marine system analysed. To facilitate the presentation of results in this article, only the structural system results are going to be presented - the remaining can be seen on .

Figure 6 presents the general asset condition dashboard. It can be seen that most of the systems onboard the unit are in good condition, as well as being well maintained according to best practices in the maintenance software. Considering the work for further operation, most of the system can be fixed during regular operation offshore, while there is a small amount that may require dry dock or yard stay.

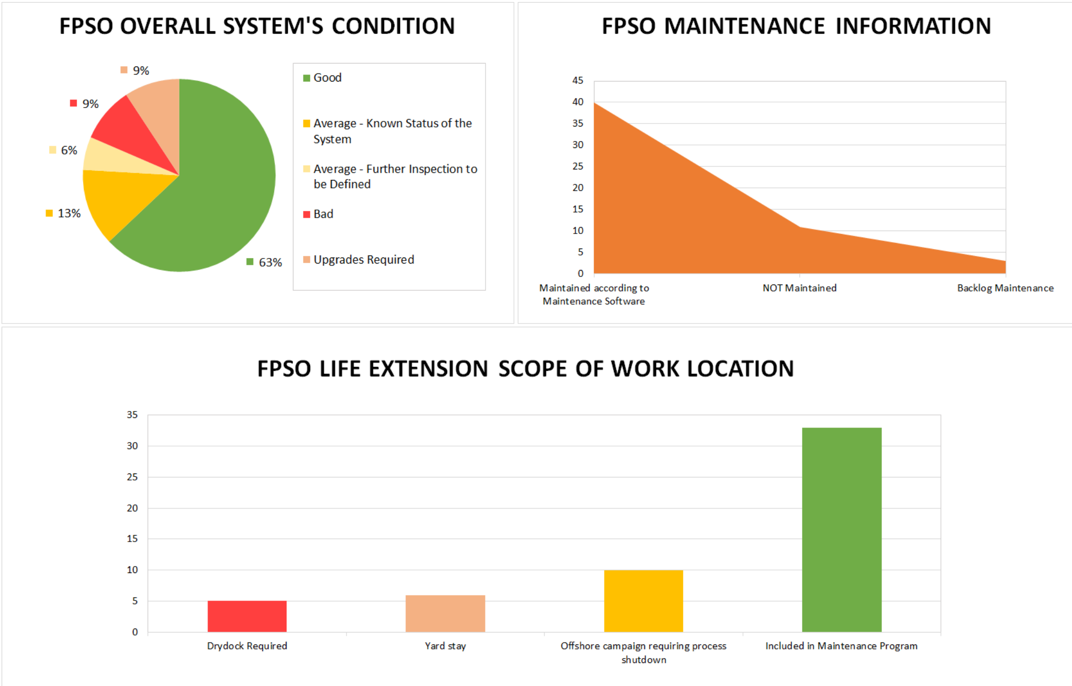


Figure 6. The FPSO General Condition .

Structural Systems

The structural systems quantitative assessment considered only the midship section. Once the unit has no turret defined, the mooring type is spread-moored and it was not possible to find data for all the subsystems, most subsystems have only qualitative assessment while the quantitative assessment is done only for the midship section.

Structural Condition

The 'As Is' condition status of the structural systems starts by defining a list of generic elements. These include the bottom and main deck, side shells, the accommodation blocks, helideck and flare. It is carried out evaluating the current condition, and then predicting a possible scope of work. The full qualitative assessment is available on Figure 7.

The results for the fictional asset shows that only the accommodation external area and its connection with the process deck are not maintained. Good condition is seen in many systems, while only the external accommodation walls are classified as bad. Some areas inside the hull are defined to be in an average condition and further inspection are necessary there. This is expected as one region is the bottom area of the tanks, while the others are the external and submerged areas of the hull.

ID	ELEMENT	INFORMATION SOURCE	USAGE	USAGE STATUS	MAINTENANCE	CONDITION	OBSOLETE	EXPECTED SCOPE	TYPE OF WORK	CRITICAL SPARE PARTS	SCOPE LOCATION
1	Overall Bottom Deck Midship	Maintenance Software	InService	Working According to Specifications	Not Maintained	Average - Further Inspection to be Defined	NO	Reinforcement of steel plates and stiffeners, as well as recoating	Life Extension	NO	Yard Stay
2	PBT	Maintenance Software	InService	Working According to Specifications	Not Maintained	Average - Further Inspection to be Defined	NO	Reinforcement of steel plates and stiffeners, as well as recoating	Life Extension	NO	Yard Stay
2	SBT	Maintenance Software	InService	Working According to Specifications	Not Maintained	Average - Further Inspection to be Defined	NO	Reinforcement of steel plates and stiffeners, as well as recoating	Life Extension	NO	Yard Stay
2	PCT	Maintenance Software	InService	Working According to Specifications	Not Maintained	Average - Further Inspection to be Defined	NO	Reinforcement of steel plates and stiffeners, as well as recoating	Life Extension	NO	Yard Stay
2	SCT	Maintenance Software	InService	Working According to Specifications	Not Maintained	Average - Further Inspection to be Defined	NO	Reinforcement of steel plates and stiffeners, as well as recoating	Life Extension	NO	Yard Stay
2	CCT	Maintenance Software	InService	Working According to Specifications	Not Maintained	Average - Further Inspection to be Defined	NO	Reinforcement of steel plates and stiffeners, as well as recoating	Life Extension	NO	Yard Stay
1	Port Side Shell - Outside Hull	Maintenance Software	InService	Working According to Specifications	Not Maintained	Average - Further Inspection to be Defined	NO	Reinforcement of steel plates and stiffeners, as well as recoating	Life Extension	NO	Drydock Required
2	PBT	Maintenance Software	InService	Working According to Specifications	Not Maintained	Average - Further Inspection to be Defined	NO	Reinforcement of steel plates and stiffeners, as well as recoating	Life Extension	NO	Drydock Required
1	Starboard Side Shell - Outside Hull	Maintenance Software	InService	Working According to Specifications	Not Maintained	Average - Further Inspection to be Defined	NO	Reinforcement of steel plates and stiffeners, as well as recoating	Life Extension	NO	Drydock Required
2	SBT	Maintenance Software	InService	Working According to Specifications	Not Maintained	Average - Further Inspection to be Defined	NO	Reinforcement of steel plates and stiffeners, as well as recoating	Life Extension	NO	Drydock Required
1	Main Process Deck Shell	Maintenance Software	InService	Working According to Specifications	Maintained	Good	NO	Regular Maintenance	Life Extension	NO	Yard Stay
2	PBT	Maintenance Software	InService	Working According to Specifications	Maintained	Good	NO	Regular Maintenance	Life Extension	NO	Yard Stay
2	SBT	Maintenance Software	InService	Working According to Specifications	Maintained	Good	NO	Regular Maintenance	Life Extension	NO	Yard Stay
2	PCT	Maintenance Software	InService	Working According to Specifications	Maintained	Good	NO	Regular Maintenance	Life Extension	NO	Yard Stay
2	SCT	Maintenance Software	InService	Working According to Specifications	Maintained	Good	NO	Regular Maintenance	Life Extension	NO	Yard Stay
2	CCT	Maintenance Software	InService	Working According to Specifications	Maintained	Good	NO	Regular Maintenance	Life Extension	NO	Yard Stay
1	Accommodation Block	Maintenance Software	InService	Working According to Specifications	Maintained	Good	NO	Regular Maintenance	Life Extension	NO	Normal Maintenace
2	Windows	Maintenance Software	InService	Working According to Specifications	Maintained	Good	NO	Regular Maintenance	Life Extension	NO	Normal Maintenace
2	Inside Decks	Maintenance Software	InService	Working According to Specifications	Maintained	Good	NO	Regular Maintenance	Life Extension	NO	Normal Maintenace
2	External Accomodation Walls	Maintenance Software	InService	Working According to Specifications	Not Maintained	Bad	NO	Regular Maintenance	Life Extension	NO	Normal Maintenace
2	Internal Accomodation Walls	Maintenance Software	InService	Working According to Specifications	Maintained	Good	NO	Regular Maintenance	Life Extension	NO	Normal Maintenace
2	Process Deck Level Plate	Maintenance Software	InService	Working According to Specifications	Not Maintained	Average - Further Inspection to be Defined	NO	Reinforcement of steel plates and stiffeners, as well as recoating	Life Extension	NO	Normal Maintenace
1	Helideck	Maintenance Software	InService	Working According to Specifications	Maintained	Good	NO	Regular Maintenance	Life Extension	NO	Normal Maintenace
2	Helideck Supports	Maintenance Software	InService	Working According to Specifications	Maintained	Good	NO	Regular Maintenance	Life Extension	NO	Normal Maintenace
2	Helideck Deck	Maintenance Software	InService	Working According to Specifications	Maintained	Good	NO	Regular Maintenance	Life Extension	NO	Normal Maintenace
1	Flare Structure	Maintenance Software	InService	Working According to Specifications	Maintained	Good	NO	Regular Maintenance	Life Extension	NO	Normal Maintenace
2	Flare Deck Support	Maintenance Software	InService	Working According to Specifications	Maintained	Good	NO	Regular Maintenance	Life Extension	NO	Normal Maintenace

Figure 7. Qualitative Assessment of Structural Components

Quantitative Model - Corrosion Assessment

The quantitative model to be use for structural systems forecasts the effects of corrosion over time - from the start of operation (Year 0 - 1995) and up to 40 years of production. The corrosion allowances were defined based on DNV GL Ship Rules - Pt.3 Ch.1 Hull Structural Design. All the ballast tanks are assumed to be coated, while the cargo tanks are coated in a region within 2m above baseline and 2m below main deck.

For the ballast tanks regions, it is considered that seawater is used, which is the same fluid that the external shells are exposed to. The corrosion rate for seawater is assumed to be 0.13 mm/year (CIMM, 2020) when it reaches the constant value. Tropical Marine atmospheric corrosion value selected is 0.51 mm/year (CIMM, 2020), and for the cargo tanks, a typical value of 0.1 mm/year was chosen (OCIMF, 1997). Figure 8 gives an overview of the fluids and in which region are they influencing in the midship section.

Two sets of lifespans are calculated based on the two requirements: corrosion allowance and renewal thickness. The results showed that most of the corrosion allowance is consumed before the renewal value is achieved, and as expected, thicker plates and stiffeners have longer life's than the thinner ones.

For the ballast tanks plates, the first corrosion allowance is consumed in 12 years, and a renewal in steel is needed in 14 years for the plates. Considering the stiffeners, the first allowance consumption happens in 17 years, and only in 29 years is steel renewal required.

For the cargo tanks, a value of 10 years is found for the first group of plates to have their corrosion allowance consumed, and 15 years to require steel renewal. For stiffeners, the results are 20 years for corrosion allowance and 35 for steel renewal.

The model predicts the effects starting on Year 0 of operation, hence in 1995, therefore a simple calculation is made for the total operation time and life extension period. Based on the assessment, the 'As Is' condition of the forecasted corrosion of the unit can be found in Figure 9. Some areas have already reached the acceptable corrosion allowance and/or require steel renewal, while others are still within the acceptable limits.

It can be seen that the model resulted in worse results for plates than for stiffeners, and this is due the type of corrosion each element is subjected too. In most cases, the stiffeners are only corroded by internal fluids of the tanks (seawater or oil), while the plates can be corroded in each side by one of the fluids and, or even the marine atmosphere.

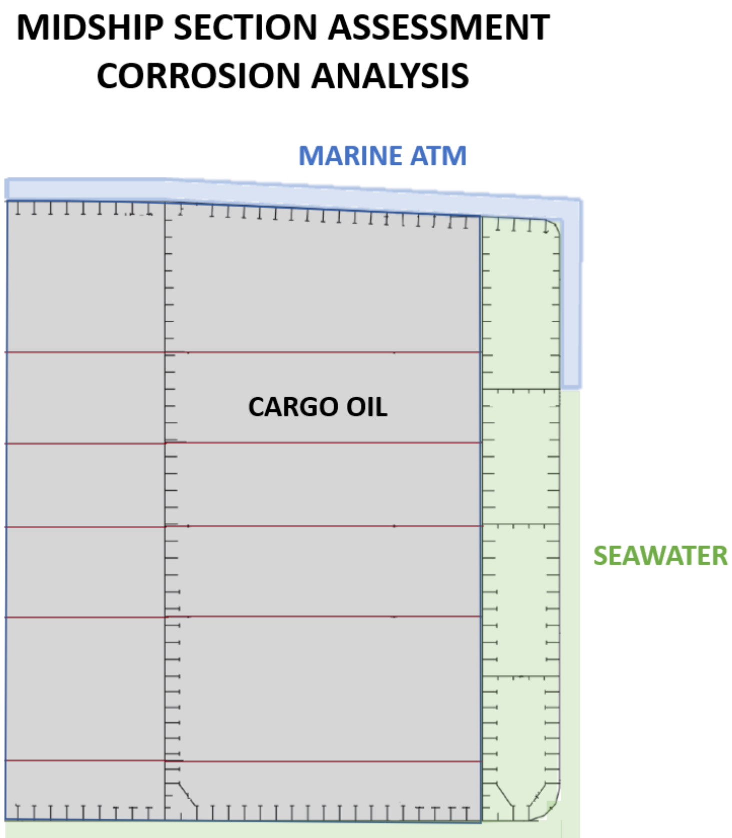


Figure 8. Fluids and Regions used in Structural Corrosion Assessment.

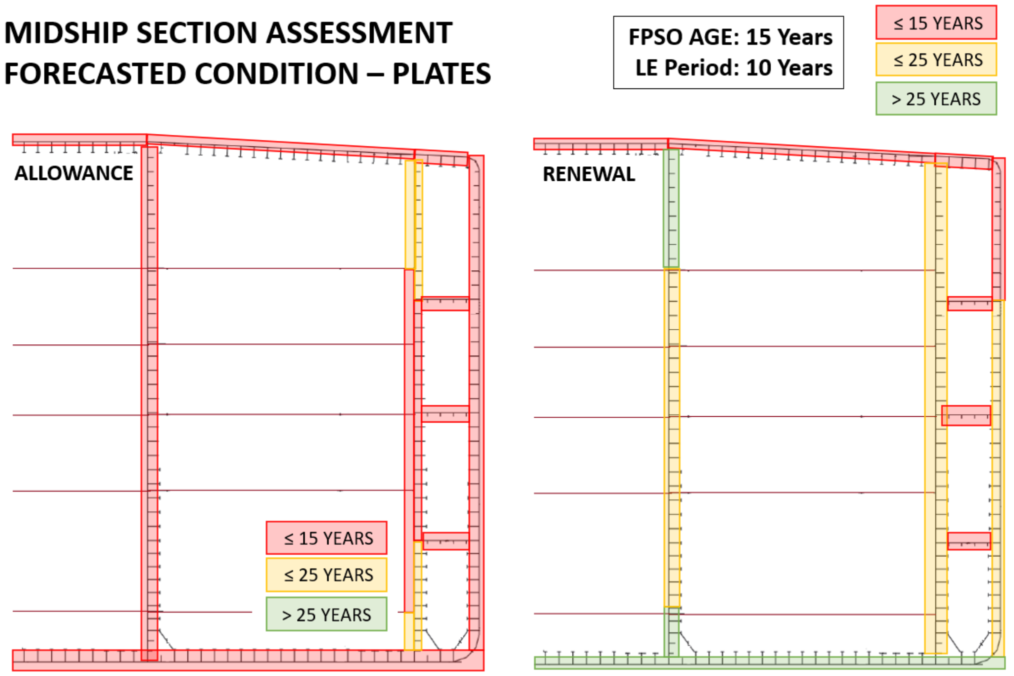


Figure 9. Midship Section Life Span - Plates.

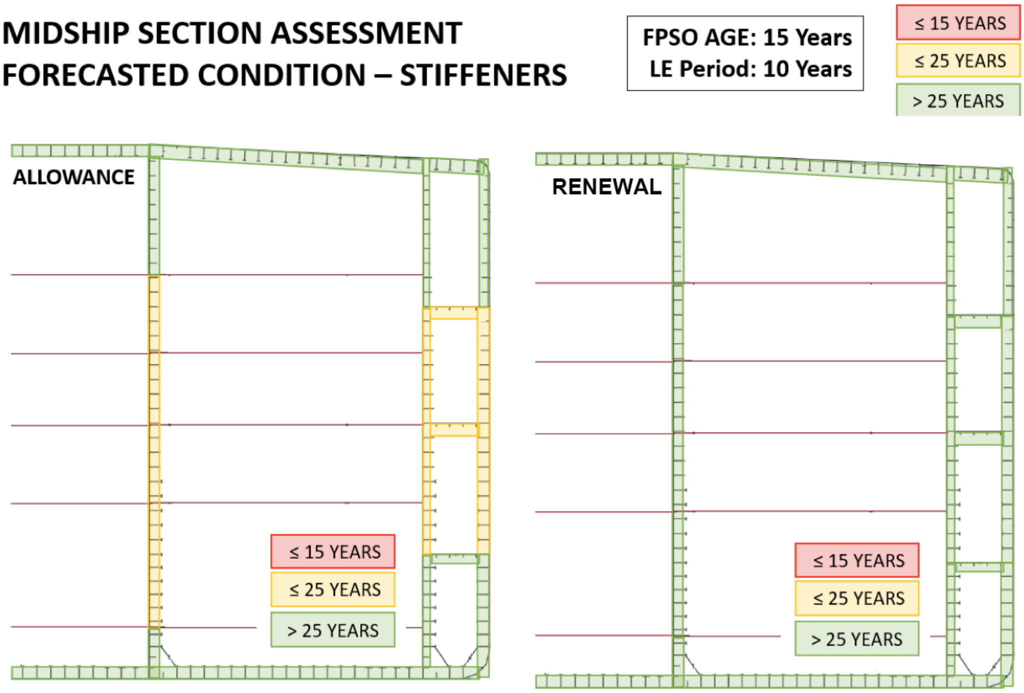


Figure 10. Midship Section Life Span - Stiffeners.

Risk Analysis and Risk Mitigation

The risk analysis starts by gathering all the information from quantitative and qualitative assessment made before into a spreadsheet. The results are presented on Table 2. Using the outcomes of "As Is" condition and corrosion forecast, the FMEA identified 3 main regions that require mitigation actions.

The first region considers the external accommodation walls that had two different risk identified - 1.3.a and 1.3.b. Both have the same failure cause: excessive corrosion/damage in accommodation, but different failure modes. The first failure mode considers the most extreme scenario, where the entire accommodation could collapse, leading to a local effect of not having a place for the crew to be accommodate in - what would lead to a stop of production. The likelihood was decided into possible and its severity would be catastrophic, hence a risk of 15 was found.

The second risk considers that the possible failure mode would be the collapse of some areas of the accommodation block. This could cause the loss of rooms for some crew members and would require that other people were assigned to fix it - what could cause delay in maintenance from other areas of the asset. This event is assumed to be possible, and the consequence would be moderate, as some other important systems could have its maintenance postponed - a risk of 9 was found, therefore within the ALARP area.

The second risk associated with the accommodation are related to the connection with the process deck level. From the qualitative assessment, it was observed that the plates are in regular condition and require some work to be renewed. Similar failure modes, effects and consequences as for the external walls were identified, where one of the risks sits in the ALARP zone and the other in intolerable area. Table 11 presents a general overview of the outcomes from the accommodation region.

REF	Element	LE Assessment Outcome	Failure Cause or Mechanism	Failure Mode	Local Effects	Global Effect	Consequences	L	S	R
1	Accomodation Block									
1.3.a	External Accomodation Walls	In bad condition, will require a full painting of the area	Excessive corrosion/damage in accommodation	Colapse of accomodation block	No place to accommodate crew	Suspention of production until problem	Loss of production days	3	5	15
1.3.b	External Accomodation Walls	In bad condition, will require a full painting of the area	Excessive corrosion/damage in accommodation	Colapse of some sections of accommodatio	Some rooms break down	People have to be assigned to fix it	People have to be accommodate somewhere else	3	3	9
1.5.a	Process Deck Level Plate	Average condition, needs more inspection and possible upgrades duuring LE period	Excessive corrosion/damage in connection level between accommodation block and	Colapse of accomodation block	Accommodation block is no longer safe - no place to accommodate crew	Suspention of production until problem is fixed	Loss of production days	2	5	10
1.5.b	Process Deck Level Plate	Average condition, needs more inspection and possible upgrades duuring LE period	Excessive corrosion/damage in connection level between accommodation block and	Cracking and breaking of some of the supporting	Supporting region corrored	People have to be assigned to fix it	Some other maintenance task may have do be rescheduled	2	3	6

Figure 11. Structural System Risk Analysis - Accommodation Outcomes.

[HTML]333333 **REF**	**System/Subsystem/Element**	**Life Extension Assessment Outcome**
1	Accomodation Block	
1.1.a	Windows	Good condition, will need some replacement during LE period
1.1.b	Windows	Good condition, will need some replacement during LE period
1.2	Inside Decks	Good condition, needs a few renewal and upgrades
1.3.a	External Accomodation Walls	In bad condition, will require a full painting of the area
1.3.b	External Accomodation Walls	In bad condition, will require a full painting of the area
1.4	Internal Accomodation Walls	Good condition, needs a few renewal and upgrades
1.5.a	Process Deck Level Plate	Average condition, needs more inspection and possible upgrades during LE period
1.5.b	Process Deck Level Plate	Average condition, needs more inspection and possible upgrades during LE period
2	Flare	
2.1	Flare Deck Support	Good condition, needs a few renewal and upgrades
3	Helideck	
3.1	Helideck Supports	Good condition, needs a few renewal and upgrades
3.2	Helideck Deck	Good condition, needs a few renewal and upgrades
4	Midship Section	
4.1	Port Side Shell	
4.1.a	Ballast Tanks Plates	Most of corrosion allowance has already been consumed. Side shell exposed to marine atmosphere already needs steel renewal, while the remaining will require within the LE Period (<25 years).
4.1.b	Ballast Tanks Stiffeners	Ballast tanks 2 and 3 stiffeners will have corrosion allowance consumed during LE Period, but no stiffeners will be below the steel renewal requirement during same period.
4.2	Starboard Side Shell	
4.2.a	Ballast Tanks Plates	Most of corrosion allowance has already been consumed. Side shell exposed to marine atmosphere already needs steel renewal, while the remaining will require within the LE Period (<25 years).
4.2.b	Ballast Tanks Stiffeners	Ballast tanks 2 and 3 stiffeners will have corrosion allowance consumed during LE Period, but no stiffeners will be below the steel renewal requirement during same period.
4.3	Bottom Shell	
4.3.a	Port Ballast Tank Plate	The forecasted model shows that the corrosion allowance has already been consumed but the renewal value is not reach withing LE Period.
4.3.b	Port Ballast Tank Stiffener	No issues to be found on the stiffeners - nor corrosion allowance, nor renewal thickness are reach during LE Period.
4.3.c	Starboard Ballast Tank Plate	The forecasted model shows that the corrosion allowance has already been consumed but the renewal value is not reached withing LE Period.
4.3.d	Starboard Ballast Tank Stiffener	No issues to be found on the stiffeners - nor corrosion allowance, nor renewal thickness are reach during LE Period.
4.3.e	Port Cargo Tank Plate	The forecasted model shows that the corrosion allowance has already been consumed but the renewal value is not reached withing LE Period.
4.3.f	Port Cargo Tank Stiffener	No issues to be found on the stiffeners - nor corrosion allowance, nor renewal thickness are reach during LE Period.
4.3.g	Starboard Cargo Tank Plate	The forecasted model shows that the corrosion allowance has already been consumed but the renewal value is not reached withing LE Period.
4.3.h	Starboard Cargo Tank Stiffener	No issues to be found on the stiffeners - nor corrosion allowance, nor renewal thickness are reach during LE Period.
4.3.i	Center Cargo Tank Plate	The forecasted model shows that the corrosion allowance has already been consumed but the renewal value is not reached withing LE Period.
4.3.j	Center Cargo Tank Stiffener	No issues to be found on the stiffeners - nor corrosion allowance, nor renewal thickness are reach during LE Period.
4.4	Cargo Tanks Longitudinal Bulkhead	
4.4.a	Port Cargo Tank Plate	Corrosion allowance is already consumed, but only the regions not coated (2m above baseline and 2m below main deck) will need steel renewal work during LE Period.
4.4.b	Port Cargo Tank Stiffener	Only the stiffeners located in the non-coated region (2m below main deck and 2m above baseline) will have corrosion allowance consumed within LE Period, but not will require steel renewal.
4.4.c	Starboard Cargo Tank Plate	Corrosion allowance is already consumed, but only the regions not coated (2m above baseline and 2m below main deck) will need steel renewal work during LE Period.
4.4.d	Starboard Cargo Tank Stiffener	Only the stiffeners located in the non-coated region (2m below main deck and 2m above baseline) will have corrosion allowance consumed within LE Period, but not will require steel renewal.

Table 2. Structural Systems Life Extension Assessment.

The midhship section is the second group that presented risks to be mitigated, divided mainly into the process deck, side shells, longitudinal cargo tank bulkhead and bottom hull. If any of those are to fail the consequences are catastrophic, as in any of theses regions crackings would cause an opening in the hull, thus water can enter the unit leading to capszing or sinking and therefore huge impacts into environment, people, reputation, asset, and operation.

From the forecasted results, it was seen that some plates already have their corrosion allowance totally consumed, while others would be consumed during the life extension period. However, the steel renewal should be kept as the main criteria for this assessment. Hence, the critical areas are the process deck level, the side shell of the hull not immersed in the ocean, and the longitudinal bulkheads separating the cargo tanks.

As stated previously, the worst case scenario is used as the consequence, while the life span guides the likelihood of each failure mode. The plates that already need (based on "As Is" condition and fore-casted corrosion) renewal have higher likelihoods of failing than the ones that will reach the renewal criteria during the life extension period.

In order to reduce the risk analysis outcomes, the assessment is made in a higher level. Therefore, it is not considered individually each result, but as hole for the defined sections. The results are presented in Figure 13.

The mitigation actions are proposed based on the risk ranking results - all the values within the in-tolerable area shall be mitigated. Although the elements are located in different regions, the mitigation action is pretty much the same: perform the necessary work so that the likelihood of a catastrophic event happening can be reduced. The risks within ALARP region have no proposed mitigation as the likelihood is the lowest. Figure 12 presents the results and reduction between initial and mitigated risks.

REF	System/Subsystem /Element	Life Extension Assessment Outcome	L	S	R	Mitigation Action	LM	SM	MR	RR
1.3.a	External Accomodation Walls	In bad condition, will require a full painting of the area	3	5	15	Perform the necessary refurbishments and apply coating in the external walls	1	5	5	0.67
1.3.b	External Accomodation Walls	In bad condition, will require a full painting of the area	3	3	9	Perform the necessary refurbishments and apply coating in the external walls	1	5	5	0.44
1.5.a	Process Deck Level Plate	Average condition, needs more inspection and possible upgrades during LE period	2	5	10	Perform the necessary refurbishments and reinforcements	1	5	5	0.50
1.5.b	Process Deck Level Plate	Average condition, needs more inspection and possible upgrades during LE period	2	3	6	Perform the necessary refurbishments and reinforcements	1	3	3	0.50
4	Midship Section									
4.1	Port Side Shell									
4.1.a	Ballast Tanks Plates	Most of corrosion allowance has already been consumed. Side shell exposed to marine atmosphere already needs steel renewal, while the remaining will require within the LE Period (<25 years).	4	5	20	Reinforce or replace as necessary. For the plates that reach criteria corrosion allowance during LE period, recoate them.	1	5	5	0.75
4.2	Starboard Side Shell									
4.2.a	Ballast Tanks Plates	Most of corrosion allowance has already been consumed. Side shell exposed to marine atmosphere already needs steel renewal, while the remaining will require within the LE Period (<25 years).	4	5	20	Reinforce or replace as necessary. For the plates that reach criteria corrosion allowance during LE period, recoate them.	1	5	5	0.75
4.5	Process Deck Level Plate	The corrosion allowance has already been consumed and the plates need steel renewal as of today.	3	5	15	Reinforce or replace as necessary. For the plates that reach criteria corrosion allowance during LE period, recoate them.	1	5	5	0.67

Figure 12. Structural System Mitigation Actions.

REF	System/Subsystem/Element	Life Extension Assessment Outcome	Failure Cause or Mechanism	Failure Mode	Detection of Failure	Local Effects	Global Effect	Consequences	L	S	R
4	Midship Section										
4.1	Port Side Shell										
4.1.a	Ballast Tanks Plates	Most of corrosion allowance has already been consumed. Side shell exposed to marine atmosphere already needs steel renewal, while the remaining will require within the LE Period (<25 years).	Corrosion damage	Cracking due to corrosion effects	Regular Inspection	Minor damage in one region	Complete Structural Colapse	Asset sinking or capsizing	4	5	20
4.1.b	Ballast Tanks Stiffeners	Ballast tanks 2 and 3 stiffeners will have corrosion allowance consumed during LE Period, but no stiffeners will be below the steel renewal requirement during same period.	Corrosion damage	Cracking due to corrosion effects	Regular Inspection	Minor damage in one region	Complete Structural Colapse	Asset sinking or capsizing	1	5	5
4.2	Starboard Side Shell										
4.2.a	Ballast Tanks Plates	Most of corrosion allowance has already been consumed. Side shell exposed to marine atmosphere already needs steel renewal, while the remaining will require within the LE Period (<25 years).	Corrosion damage	Cracking due to corrosion effects	Regular Inspection	Minor damage in one region	Complete Structural Colapse	Asset sinking or capsizing	4	5	20
4.2.b	Ballast Tanks Stiffeners	Ballast tanks 2 and 3 stiffeners will have corrosion allowance consumed during LE Period, but no stiffeners will be below the steel renewal requirement during same period.	Corrosion damage	Cracking due to corrosion effects	Regular Inspection	Minor damage in one region	Complete Structural Colapse	Asset sinking or capsizing	1	5	5
4.3	Bottom										
4.3.a	Port Ballast Tank Plate	The forecasted model shows that the corrosion allowance has already been consumed but the renewal value is not reached withing LE Period.	Corrosion damage	Cracking due to corrosion effects	Regular Inspection	Minor damage in one region	Complete Structural Colapse	Asset sinking or capsizing	1	5	5
4.3.b	Port Ballast Tank Stiffener	No issues to be found on the stiffeners - nor corrosion allowan, nor renewal thickness are reachead during LE Period.	Corrosion damage	Cracking due to corrosion effects	Regular Inspection	Minor damage in one region	Complete Structural Colapse	Asset sinking or capsizing	1	5	5
4.3.c	Starboard Ballast Tank Plate	The forecasted model shows that the corrosion allowance has already been consumed but the renewal value is not reached withing LE Period.	Corrosion damage	Cracking due to corrosion effects	Regular Inspection	Minor damage in one region	Complete Structural Colapse	Asset sinking or capsizing	1	5	5
4.3.d	Starboard Ballast Tank Stiffener	No issues to be found on the stiffeners - nor corrosion allowan, nor renewal thickness are reachead during LE Period.	Corrosion damage	Cracking due to corrosion effects	Regular Inspection	Minor damage in one region	Complete Structural Colapse	Asset sinking or capsizing	1	5	5
4.3.e	Port Cargo Tank Plate	The forecasted model shows that the corrosion allowance has already been consumed but the renewal value is not reached withing LE Period.	Corrosion damage	Cracking due to corrosion effects	Regular Inspection	Minor damage in one region	Complete Structural Colapse	Asset sinking or capsizing	1	5	5
4.3.f	Port Cargo Tank Stiffener	No issues to be found on the stiffeners - nor corrosion allowan, nor renewal thickness are reachead during LE Period.	Corrosion damage	Cracking due to corrosion effects	Regular Inspection	Minor damage in one region	Complete Structural Colapse	Asset sinking or capsizing	1	5	5
4.3.g	Starboard Cargo Tank Plate	The forecasted model shows that the corrosion allowance has already been consumed but the renewal value is not reached withing LE Period.	Corrosion damage	Cracking due to corrosion effects	Regular Inspection	Minor damage in one region	Complete Structural Colapse	Asset sinking or capsizing	1	5	5
4.3.h	Starboard Cargo Tank Stiffener	No issues to be found on the stiffeners - nor corrosion allowan, nor renewal thickness are reachead during LE Period.	Corrosion damage	Cracking due to corrosion effects	Regular Inspection	Minor damage in one region	Complete Structural Colapse	Asset sinking or capsizing	1	5	5
4.3.i	Center Cargo Tank Plate	The forecasted model shows that the corrosion allowance has already been consumed but the renewal value is not reached withing LE Period.	Corrosion damage	Cracking due to corrosion effects	Regular Inspection	Minor damage in one region	Complete Structural Colapse	Asset sinking or capsizing	1	5	5
4.3.j	Center Cargo Tank Stiffener	No issues to be found on the stiffeners - nor corrosion allowan, nor renewal thickness are reachead during LE Period.	Corrosion damage	Cracking due to corrosion effects	Regular Inspection	Minor damage in one region	Complete Structural Colapse	Asset sinking or capsizing	1	5	5
4.4	Cargo Tanks Longitudinal Bulkhead										0
4.4.a	Port Cargo Tank Plate	Corrosion allowance is already consumed, but only the regions not coated (2m above baseline and 2m below main deck) will need steel renewal work during LE Period.	Corrosion damage	Cracking due to corrosion effects	Regular Inspection	Minor damage in one region	Complete Structural Colapse	Asset sinking or capsizing	2	4	8
4.4.b	Port Cargo Tank Stiffener	Only the stiffeners located in the non-coated region (2m below main deck and 2m above baseline) will have corrosion allowance consumed within LE Period, but not will require steel renewal.	Corrosion damage	Cracking due to corrosion effects	Regular Inspection	Minor damage in one region	Complete Structural Colapse	Asset sinking or capsizing	2	4	8
4.4.c	Starboard Cargo Tank Plate	Corrosion allowance is already consumed, but only the regions not coated (2m above baseline and 2m below main deck) will need steel renewal work during LE Period.	Corrosion damage	Cracking due to corrosion effects	Regular Inspection	Minor damage in one region	Complete Structural Colapse	Asset sinking or capsizing	2	4	8
4.4.d	Starboard Cargo Tank Stiffener	Only the stiffeners located in the non-coated region (2m below main deck and 2m above baseline) will have corrosion allowance consumed within LE Period, but not will require steel renewal.	Corrosion damage	Cracking due to corrosion effects	Regular Inspection	Minor damage in one region	Complete Structural Colapse	Asset sinking or capsizing	2	4	8
4.5	Process Deck Level Plate	The corrosion allowance has already been consumed and the plates need steel renewal as of today.	Corrosion damage	Cracking due to corrosion effects	Regular Inspection	Minor damage in one region	Complete Structural Colapse	Asset sinking or capsizing	3	5	15

Figure 13. Structural System Risk Analysis - Midship Section Outcomes.

WORK PACKS AND COST ESTIMATION

To create the work packs, Butler (2012) is used as reference, once the author provides guidelines on how to estimate ship repair in man-hours. For steel and pipe works, the author defines that it includes both labor and material. Therefore, relating the dimensions with density it was possible to find a weight. The typical rate of a ship yard was not possible to find, but different sources present values of salaries in the shipbuilding industry. Selecting wages presented by Shuker (2018) as a starting point, the average salary in a Chinese shipyard is set to 1245 USD/month. Considering a work journey of 40 hours per week, this gives a value of approximately 8 USD/hour.

In order to define a yard man-hour rate, it was decided to use a profit margin of 25 %, hence a rate of 10 USD/man-hour is selected for the analysis. Again, this is a rough estimation but considered enough for the objective of this assessment. The steel price, whenever needed was set to be 435 USD/tonnes (SteelBenchmarker, 2020).

The first work pack, WP1 - Steel Renewal, gathers all the structures and elements that require fabrication work. The life extension methodology assessed plates and stiffeners, but only considering their thickness values. The rates proposed by Butler (2012) calculate man-hours per tonnes, hence it was necessary to define the dimensions of each plate and stiffeners that required steel works.

Another result of the corrosion model considering only the thickness is that it predicts a constant scenario. One cannot assume that all the elements with same thickness will be affected at the same pace, therefore a coefficient to define what is the percentage of those plates that actually require steel work is used. In a real life scenario, these coefficients can be optimized by inspections. The total steel weight renewal was calculated to be almost 20.000 tonnes and a cost of 24 MUSD was found.

WP2 - Hull Painting describes the painting work to be performed in the external areas of the hull. The submerged area is decided not to be painted, but anodes shall be replaced there (treated in another WP). Thus, to determine the external area of the hull that shall received painting treatment the required areas were exported from the 3D model - same process was done for accommodation region and process deck area. Due to lack of information, a rate of 10 USD/m2 was selected. This assessment considers that almost 30.000 m2 required painting, at a total cost of about USD 300.000. However, this value represents just the core paint work itself, and does not include the prices in case this has to be done in the yard or offshore

Anodes replacement are presented in WP 3. In order to predict the total man-hours required, the total weight of anodes was calculated as function of underwater hull area. A replacement frequency of 5 years is assumed, and a general weight of 10 kg requiring 1.5 man-hours per kg was selected. The rate of 10 USD/man-hours was used again and a value of approximately USD 30.000 is calculated for WP3.

Firefighting assessment showed that some valves were in bad condition and required repair. With the objective to cost the work pack, it is defined that 20 valves with 150 mm bore require the overhaul, and using the same rate as before, a value of USD 2.300 is found for this work pack.

The hypothesis used during the life extension assessment assumed that, as the pipes reached the criteria they were substituted. Hence, there is no need to replace any of the pipes analysed now - only when they reach the criteria during the life extension period. No work packs for pipes are created.

The offloading hose replacement is covered by WP5. A value of USD 200.000 was selected for the work. The main engines overhauls are covered by WP6, and the calculations are made based on the decisions of what systems shall be overhauled. Most dimensions and quantities for the calculations were found in Wartsila 46DF product guide, but whenever necessary assumptions were made to be able to cost the work pack. To overhaul all the defined components before entering the life extension period, over 17.000 man-hours are required, at a total cost of USD 178.000 - for the 6 main engines.

Painting of all ballast tanks and the required areas in cargo tanks are covered by WP 8, and it assumes the same methodology as WP 2. The cargo tanks areas to be painted are calculated considering the hypothesis that only 2m above baseline and 2m below deck level are required to be painted, and a total cost of over USD 500.000 was estimated.

All the work packs created are presented in Table 3. It is important to notice that these work packs do not contain all the work required for the fictional FPSO. For instance the scope of work for control and telecommunication system is not included, as it was not possible to find values for it. Also, it is just an estimation and the rates are not representing the reality.

Workpack	**Description**	**Location**	**Cost**
WP 1 - Steel Renewal	Steel Renewal of Plates and Stiffeners	Yard Stay	$ 23,858,994.38
WP 2 - Hull Painting	Painting of External Hull Areas	Yard Stay	$ 292,486.09
WP 3 - Anodes Replacement	Replacement of Anodes in Underwater Area of the Hull	Yard Stay	$ 29,503.67
WP 4 - Firefighting Valves Replacements	Replacement of Valves that are in bad condition from Firefighting Systems	Yard Stay	$ 2,300.00
WP 5 - Offloading Hose Replacement	Replacement of Offloading Hose	Yard Stay	$ 100,000.00
WP 6 - Overhaul Main Engine	Overhual of Main Engines	Yard Stay	$ 177,773.87
WP 7 - Overhaul of Pumps	Overhaul of firefighting and cargo pumps	Yard Stay	$ 5,856.00
WP 8 - Tank Painting	Painting of Internal Areas in Ballast Tanks and required areas of Cargo Tanks	Yard Stay	$ 555,560.00
Total Cost			**$ 25,022,474.01**

Table 3. Life Extension - Work Packs Cost.

ECONOMICAL FEASIBILITY ANALYSIS

The decision of whether the unit is suitable for life extension or not is based on a economical framework. For this analysis, it is assumed that the cost for the company are CAPEX and OPEX. CAPEX is the initial investment cost, therefore all the money that has to be invested in the unit to make it suitable for life extension, while OPEX is related to the operational cost to keep the unit running. The only source of income analysed here is the rate the company receives with the asset, hence the charter rate for the FPSO.

OPEX costs tend to increase as the unit gets older, because more systems will require maintenance and even replacement, however as a simplification for this master thesis it is kept constant. Also, the shipowner/operator will probably required financing to obtain the necessary CAPEX value, and that should be considered in the analysis.

The information provided by Kurniawati et al. (2016) in the article “Long-term FSO/FPSO Charter Rate Estimation” is used as reference to perform the feasibility analysis of the life extension project. The author provided OPEX data for a 261m long FSO. A simple linear analysis using the units lengths was performed to define the rates for the fictional FPSO, rounding up the values for a better visualization later on - the results are presented in Table 4. The FPSO has an initial OPEX rate of USD 1,119,200.00 per year. Many factors affect the OPEX of the asset during its life, however to simplify the analysis, it is considered constant throughout the life extension period.

-2* **OPEX ESTIMATION**	**Kurniawati et al. (2016)**	**Thesis FPSO**	
	USD/year	**Estimated USD/year**	**Selected USD/Year**
Crew	$ 201,196.00	$ 241,049.77	$ 242,000.00
Maintenance and Repairs	$ 50,000.00	$ 59,904.21	$ 60,000.00
Administration and Genral Charges	$ 25,000.00	$ 29,952.11	$ 30,000.00
Lub Oil	$ 6,000.00	$ 7,188.51	$ 7,200.00
Insurace	$ 600,000.00	$ 718,850.57	$ 720,000.00
Provisions and Stores	$ 50,000.00	$ 59,904.21	$ 60,000.00
Total Operating Cost (USD/Year)	$ 932,196.00	$ 1,116,849.38	$ 1,119,200.00

Table 4. FPSO OPEX Estimation.

The CAPEX value of a life extension or redeployment project varies depending upon the condition of the unit and location of field for extended operating time. Evans (2017) presented cost impact values for EnQuest Producer of over 200 MUSD. Offshore-Mag (2017) states that Petrojarl I costed 183 MUSD to be redeployed for Brazil, and that Petrojarl Varg is expected to have upgrade costs ranging from MUSD 100 - MUSD 400.

The cost for the work packs defined was estimated to be about MUSD 25. As explained before, it does not consider all the work required for the marine systems, even the less is a full approximation of the total cost considering yard work. Therefore, it was decided to define some factors and some hypothesis were made that could return a CAPEX value within a range of MUSD 100 - MUSD 200. The defined work packs are set to represent 20 % of the total work needed, which represents 80 % of the CAPEX for the FPSO. Thus, a CAPEX value of MUSD 157 is found for this assessment.

The shipowner/ship operator has a budget of 30 % and needs to finance the rest, hence approximately MUSD 110. The same interest rates as presented by Kurniawati et al. (2016) is selected, 10 %/year, and the financing period is the same as life extension (10 years), Using a simple financing technique (assuming constant annual payments and interest rates, and not considering depreciation or inflation), the company has to pay USD 17,816,279.31 per year during the life extension period. The value invested by the company is diluted over the life extension period, thus considered as a annual expenditure.

Another parameter necessary to assist in the decision making is the value of selling the vessel for scrap. A rate of 375 USD/LDT (LDT - Light Displacement Tonnes) is used based on rates from Roussanoglou (2019). Using the regression analysis presented in Appendix **??** - FPSO Description, the FPSO has an estimated LWT of 40.190 ton, hence a total value of around MUSD 15 (USD 15.071.250,00) can be expected if it sold for scrap.

The FPSO operating days per year is assumed to be 360 days, and the profit margin is defined to be variant over the life extension period. As the end of the period is reaching, the profit margin is lowered, and the selected values are presented in Figure 14.The profit margins are used to calculate the minimum required charter rates for the project to be over the annual expenditures, and those are defined as unique for each extended operational year.

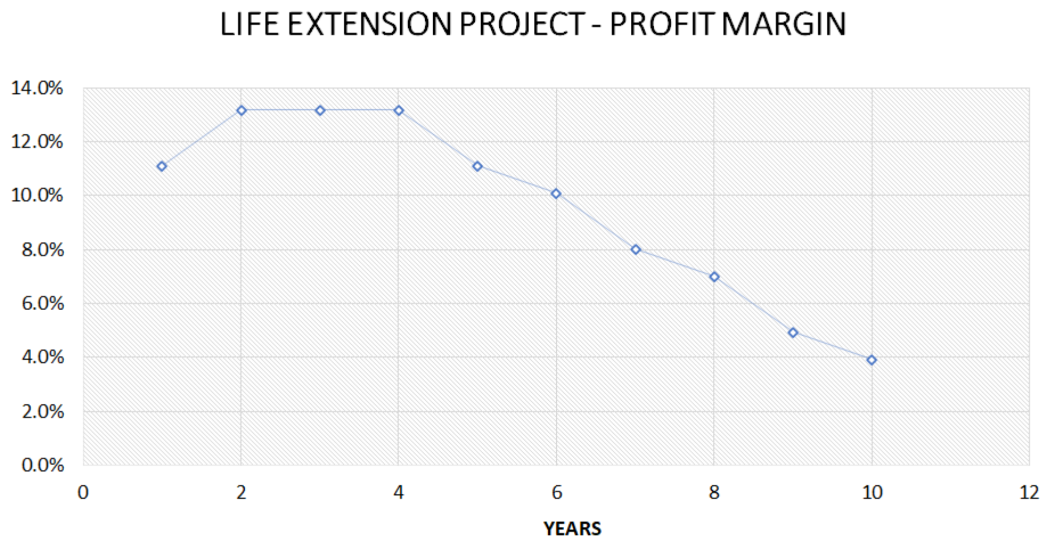


Figure 14. Profit Margin for Life Extension Period.

For this master thesis, it is set that the life extension project is only suitable if the shipowner gets back 50% more than selling the unit. Hence, the total revenue required over the 10 years period is known and the model is recalculated to find the required charter rates to achieve this goal. Table 5 presents the values for charter and Figure 15 gives an overview of the economical framework results.

YEAR	CHARTER RATE	REVENUE
1	$ 72.923,61	$ 2.625.305,54
2	$ 74.274,04	$ 3.111.462,92
3	$ 74.274,04	$ 3.111.462,92
4	$ 74.274,04	$ 3.111.462,92
5	$ 72.923,61	$ 2.625.305,54
6	$ 72.248,39	$ 2.382.226,85
7	$ 70.897,95	$ 1.896.069,46
8	$ 70.222,73	$ 1.652.990,77
9	$ 68.872,30	$ 1.166.833,39
10	$ 68.197,08	$ 923.754,69
	TOTAL	$ 22.606.875,00

Table 5. FPSO Charter Rates Based on Required Revenues.

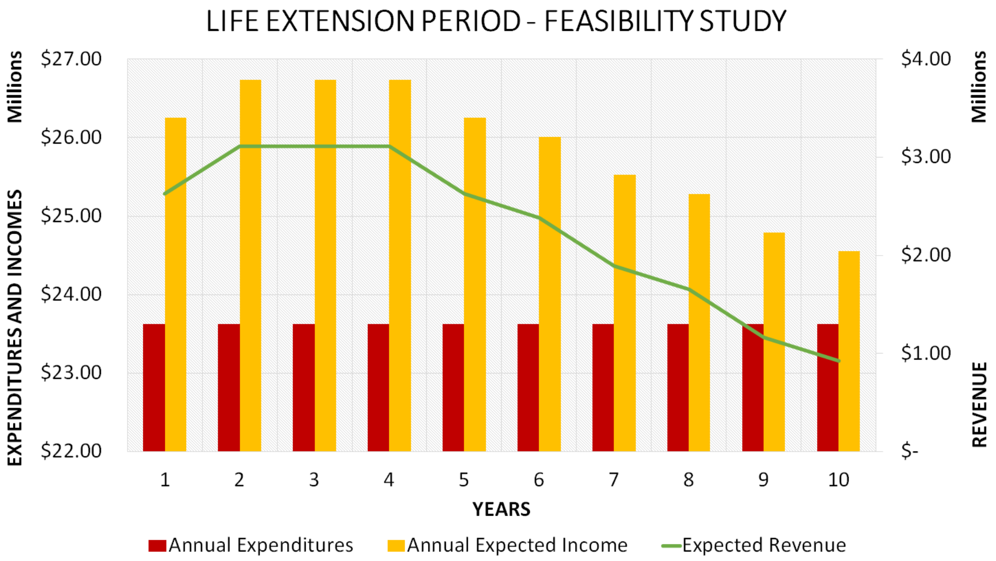


Figure 15. Forecasted Economical Framework for Life Extension Period.

To check whether these rates are achievable, an analysis considering the oil price and production forecast is made. As in May 2020, the world is suffering from the corona crisis that has heavily hitten the oil industry, with oil prices going even negative. Obviously, this is not something that shall last forever, and as presented in the introduction before, the oil price changes in a cyclic behaviour and hence, sometime the oil price will recover. At the time of this assessment (08/05/2020), the brent crude oil price is just around USD 30.00 per barrel - in position to June 2019, where the price was around USD 70.00.

In the offloading analysis made before, it was detailed that the FPSO had been responsible for 25% of the field production for over the last 15 years of operation. For the life extension period, it shall be responsible for the same amount - 25% of the production. Hence, it is predicted that the FPSO will offload 521.840.500 barrels.

For this assessment, the thinking is done considering the company chartering the FPSO, and not FPSO owner anymore. Hence, keeping the assumption that they would charter the asset 360 days per year, the amount of daily production can be calculated and compared to the FPSO processing capacity to check whether it would still be a fit - the results are presented on Figure 16.

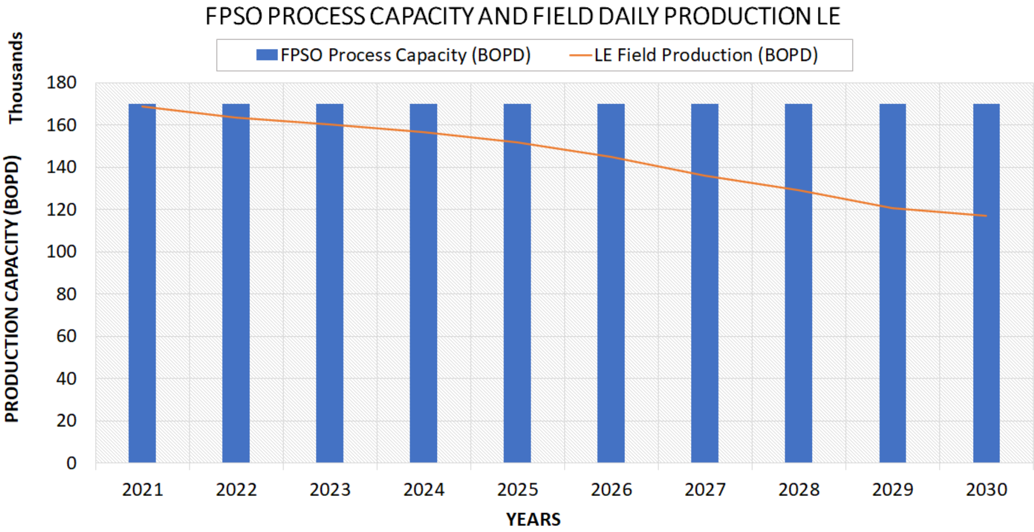


Figure 16. Field and FPSO Production Capacity during Life Extension Period.

From the total sales price, the oil companies should be able to pay all the required rates with exploration, transportation, FPSO charter, salaries, provisions and so on, while making a descent profit. Therefore, a fraction of total sales is destined to rent the FPSO and to pay all the necessary taxes related to it. Assuming that only 1% of total forecasted sales value is destined for chartering expenses, that the predicted production will actually occur, and considering the minimum rate calculated for the FPSO owner to have the defined profit during life extension period, one can predict what is the minimum average oil price rate required for each operational year.

For this project to be viable with all the hypothesis and assumptions made, the oil price will need to be at least USD 43.17 at the start of life extension period, reaching up to USD 58.19 in the last year. Based on the oil price history, these values are not outside typical variation rates, but the current world situation leaves an uncertain scenario of whether the prices will pick up again soon. Hence, with the current brent price of around USD 30.00, the life extension project is not feasible.

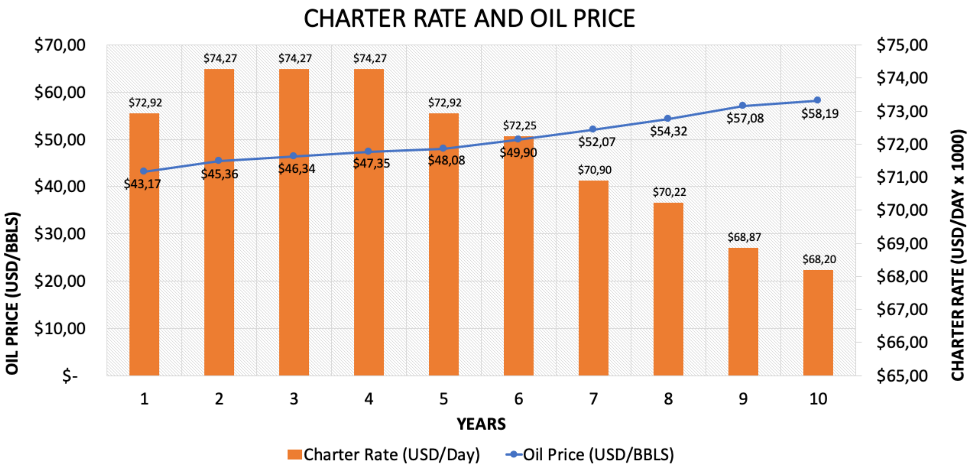


Figure 17. Minimum Oil Price for Project Viability.

ANALYSIS OF THE RESULTS

During the development of the methodology and testing out the models into a FPSO, many challenges were faced. Deciding upon main dimensions and performing naval architecture calculations was somewhat a straight forward process with wide available literature and guidelines. However, the FPSO requires more work than a regular merchant vessel.

It is not only a ship, but also a factory for processing oil. Hence, different disciplines and knowledge is involved while designing it. The marine systems selected for the study also had different degree of difficulties for their definitions. Some have a wide variety of information online and in books, such as the vessel's midship section and diesel engines, while others require a full assessment on their own - like the piping system.

As a result, some of the studied systems are well defined and accordingly to real life scenarios, while others can be with over dimension's and not a true representation of that systems. Also, when doing a life extension methodology, the current condition of the unit is considered and not the design life. Initially, this was also the objective of the study - using current values that could be available on inspection reports - notwithstanding, as the information started to be gathered for testing, it was seen that it was not possible to define the values as current condition because they were more related to fabrication characteristics. To solve this problem, the results were used as reference and replacement criterion were selected - if the results reached the criteria within the first operation time frame (15 years), they were substituted. Therefore, their initial life is started again and the current value could be found.

Before testing out the proposed models, many assumptions were necessary. Defining the oil field in a tropical area gives information into corrosion effects, which are expected to be high. However, selecting accurate corrosion rates was very complicated, once it depends in many effects such as temperature, fluid type and velocity. Coating life also influences how corrosion happens, hence it was included into the analysis based on coating area coverage found in DNV RBI guidelines. Although the guidelines are for topside rotating equipment, the same process was kept for all the steel components - structural steel plates, stiffeners, and pipes.

The rotating equipment also required an operational profile. In reality, the same group of equipment does not run at similar pace - some runs for longer while others are used less. Accordingly, an operational profile was defined both for offloading frequency and power generation. This resulted in different overhauls time frames for the systems, which are closer to the real condition of a vessel operating offshore.

The risk analysis performed was solely qualitative, and keeping the mindset for worst case scenario always. This was necessary to limit the amount of hazards found, because if each system was to be evaluated in a complete detail, the assessment would be huge. Hence, keeping in the mind the worst that could happen during life extension period if the system's condition was kept resulted in a conservative assessment.

With the scope of work for life extension delineated, work packs were created. This was done based on guidelines available in the literature, hence the total man-hours should be a good approximation of reality. However, the yard rates used were based on information from wages in Chinese shipyards, and may not represent the actual value that is charged.

The economical analysis also required different sorts of hypothesis and assumptions, including assuming profit rates, constant charter rates, scrap selling values and so on. It included assessments made for the two main stakeholder in FPSO leasing: the company that owns and operates the vessel, and the oil company that will use it. The project feasibility was measure as an oil price value: the minimum value for the project to be profitable for both companies during the life extension period was found. This is an important indicator for decision-makers to conclude whether the project is feasible or not.

Eventhough many assumptions and hypothesis were required during the case study, and with the possibility of over dimensioned systems, the models worked and the methodology proved to be efficient. The final result - the oil price to have a profitable project - ranges from USD 43.17 to USD 58.19 which is a realist price based on past rates.

When analysed individually, the hypothesis and assumptions made might be outside of the reality and can definitely be improved. However, it is the global impact into the project assessment that is important. Based on the results for the oil price range, it is safe to conclude that the methodology can be used for real life scenarios.

CONCLUSION AND RECOMMENDATIONS FOR FURTHER WORK

The oil and gas industry is an important stakeholder for different sectors of the economy. In one way or another, everyone is affected by it - it can be the fuel used to power our vehicles, the gas people use to cook, or somebody we know that works within its supply chain. Oil price is the main factor shaping the industry, with ups and downs happening in a cyclic behaviour.

As in 2020, the world is experiencing a terrible scenario, with very low oil price rates. This affects directly oil exploration projects - lower prices do not make it attractive to build new offshore structures nor explore new oil fields. From previous years, when the oil prices start to recover, a trend in the industry can be observed - utilizing existing facilities at the same oil field or redeploying it to another location.

One of the master thesis objective was to investigate the possibility of creating a methodology to assess life extension of FPSO units, and it can be concluded that it is possible to do so. Considering the decommissioning phase of the unit's life cycle, it was seen that an important factor to be addressed is the asset condition.

Depending upon the vessel's condition, the amount of work required to achieve enough compliance that allows for longer operation is not viable at all - it can even be higher than building a new ship. However, most FPSOs can experience at least a redeployment or life extension project during its life cycle.

Therefore, it is necessary that companies can keep up with the asset's condition in order to maintain time in production and safety high, and also performing faster and accurate life extension and redeployment studies. The methodology proposed by this thesis utilizes concepts that are already used and organize them into different models. Qualitative condition assessment and remaining useful life are concepts widely studied and used in the process industry. The qualitative tool that gathers the necessary information about the current asset condition is powerful for life extension work - all the information needed is grouped into one place. Hence, the access is easy and fast, and should be accurate as long as it is updated. Nevertheless, all the models created are tested out and information available is organized for marine systems and subsystems.

Predicting the remaining life gives important information to decision makers, as they can forecast what would the actual condition of systems be during the extended operational time. Therefore, they can decide more precisely what is the extend of work required and what systems will need full replacement. These values also allow for a risk analysis - the likelihoods and consequences hazards can be optimized based on life and condition assessments. Most of the risks found for life extension are in relation to system failure, and they can be mitigated by performing the necessary refurbishments and replacements before entering the new operational time.

As most projects, the final decision parameter when doing the life extension project is money. To assess it, the scope of work is transformed into work packs that are later costed. Depending on the investment prices and the predicted revenues, the project is considered feasible or not. To validate the methodology and provide input to the decision-making, a economical feasibility analysis was performed considering two stakeholder of the offshore industry: shipowner/operator and oil company. For shipowner/operator, the decision-making can be done considering the minimum required charter rate to achieve a set of goals, while for the oil company the analysis is performed by estimating what would be the revenue with oil barrels sales. The final result is a minimum oil price required for the project to be profitable for both stake-holders.

The master thesis was developed into 3 main areas - research, methodology development and case study. Although they were presented in a linear structure, all the process iterate with each other. While developing the models to be tested, it was necessary to run into literature to review the concepts and decide upon hypothesis.

Selecting a FPSO for the study was very challenging. Ships have been around for a long time, but FPSOs are somewhat new - the first one came around late 1970s. In shape, they resemble a big oil tanker, but they also have a factory on their main deck.

Different studies have been done about FPSOs and processes linked to them. Even so, most of the assessment are made for specific systems instead of the entire unit. Defining a size, shape and basic naval architecture parameters was easy, but describing fully all the systems onboard the unit was very challenging. Not withstand, the quantity of systems to make a floating production work properly is huge, thus a screening factor was needed to select what systems would be studied. The focus should be the marine systems, as they are closer to the master program Ship Design, and the selection was guided based on availability of information.

The structural midship section, the firefighting system, offloading system, power generation system and electronic systems were the selected ones for the thesis assessment. However, for some subsystems the definitions were based on best guesses. The piping system dimensions, for instance, were selected from available suppliers online, but could be with wrong dimensions.

A life extension assessment is done after the unit has operated for longer, hence should use current data about the unit. When predicting the corrosion effects over steel plates, the correct manner is using thickness from inspection reports. However, the data used in the thesis is from design and fabrication values, therefore the models were adapted and criterion were used so that the assessment could actually predict remaining useful life.

The corrosion rates also turned out to be a real challenge. It is not possible to have only one steel corrosion rate for one type of fluid, as different factors affect it. Hence, the values used on the thesis are merely a estimate and should be used cautiously. Ideally, the models should have been tested with thickness values from inspection reports and corrosion rates based on experiments for that specific location.

The cost analysis is performed in a simplified manner, pricing work packs and by a economical analysis considering CAPEX and OPEX. Although the final outcome of the analysis were oil prices within realistic rates, different judgments were made for profit rates and charter rates that could be optimized to represent a more realistic business case.

Looking back into past oil prices, the range is not out of a normal and expected scope. Consequently, it is acceptable to say that the methodology has proved to work and could be used in a real case scenario. All the work that was performed individually, when brought together delivered acceptable results. Thus, proportionally the values selected are good and the hypothesis are balanced, but individually they might need to be optimized.

This master thesis addressed different topics, and hence creates the possibility of various future development. Addressing the case study, it was tested out with a mock up FPSO - with systems defined from various sources and different hypothesis and assumptions were made. As a suggestion, the methodology could be applied in a real FPSO, thus using real data.

The systems studied were only some of the marine systems, therefore further work can be done including the process systems. This allows for the development of more quantitative models with different degradation mechanisms.The risk analysis was done in a qualitative way, but it is possible to also extend it for a quantitative assessment. This could include for instance probability data on failure rates, event and fault tree analysis, and Bayesian belief networks. The created models can also be used to predict maintenance schemes, as they give an overview of what systems will need more work during the operational phase.

Optimization is also an outcome that could be performed, studying what would the minimum and maximum profit margin to be achieved for a life extension project. This methodology can also be used to address what type of system are driving most of the work in life extension and using it as a lessons learned. It can give input to companies on how to adapt their maintenance strategies focusing on extending the life of the assets.

Lastly, each of the quantitative models can be developed further into more detailed levels. For example the corrosion models can be updated and calibrated with information from risk based inspection. Experimental work on corrosion rates can also be done, as more realistic values could be used for the specific region where the FPSO is located. The models can also be developed to integrate with other engineering techniques - such as finite element analysis of the hull girder - what would provide for more accurate results from the early phases of a life extension project.

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