FMEA of Catenary Mooring Systems for Floating Offshore Wind Turbines - Insights from FPSOs

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Preface

For the finalization of our time as students in Ocean Technology, we convey this bachelor thesis. This report is written by students at the Department of Mechanical and Marine Engineering (IMM) at Western Norway University of Applied Science (HVL). During the development of this BSc thesis, we researched and enhanced our abilities in the Operations and Maintenance course. The assignment was granted to us by Vattenfall Vindkraft A/S. We acknowledge Dariusz Eichler and Nadir Azam, from Vattenfall Vindkraft for their guidance, knowledge, and advice throughout the project. They have been essential throughout the progress of this report and aided in gathering information and connecting us to the industry. Additionally, we would like to acknowledge MARIN and Pieter Aalberts for assisting us in refining our thesis and insights of great value to this report. We would also like to acknowledge the aid of Øystein Gabrielsen for his time and the information given, which was of great value to the report. Lastly, we express our recognition and appreciation to our advisor, Professor Maneesh Singh, for his expertise, insights, and support throughout our research progress.

Abstract

To conduct a Failure Mode and Effect Analysis (FMEA) for a catenary mooring system for a Floating Offshore Wind Turbine (FOWT), the thesis needed historical data available to support a solid foundation. From gathering information and collecting data in the early stages of the thesis, we learned that there is little to no specific data to support our thesis. However, the research brought us to the historical data from FPSOs and semisubmersible Oil and Gas (O&G) rig's mooring systems. From a meeting with MARIN [1], we got confirmation that the mooring systems for FPSOs and FOWT are very similar. Investigating the multiple components for both FPSOs and FOWT, we were able to select five components that were essential and commonly used for both FPSO and FOWT, see Figure 2-4. There are some differences between the two that need to be addressed. The technical differences between an FPSO and a FOWT are substantial but, at the same time, not crucial for the statement that an FMEA for an FPSO cannot be used for a FOWT. The differences include different water depths and hydrodynamical forces, also known as weight distributions and loading. Since FOWT is in the early development stage, several unknown variables exist. The materials and components operators utilize in their FOWTs vary from company to company. Addressing this, makes it difficult for this FMEA to be relevant, but it is important to note that the failure modes for a FPSO will be the same for a FOWT if the components are the same. For example, a chain link will be the same in both cases. We know that the catenary mooring system is subjected to very different conditions. Still, the failure cause will eventually lead to the same failure mode and profiles for each component. For future recommendations and the possible evolution of the catenary mooring systems applied by FOWTs, we have seen that the experience and historical integrity of most of the components from FPSOs is applicable to FOWTs with awareness of different environmental conditions. This FMEA can be a foundation for future work on the mooring system with the correct data set and the proper alterations regarding the initial conditions, such as loading, environment, and operational variables. This project aims to complete a comparative study between FPSOs and FOWTs and find positive results, focusing on transferring knowledge from the O&G industry and taking advantage of the experience and lessons learned. With respect to the Operations and Maintenance (O&M) of mooring systems for FOWTs, it appears that components such as buoyancy buoys and clump weights can cause challenges. Numerous components of these types will complicate installations, and in case they need replacement, this will be even more complicated.

Sammendrag

For å utføre en Feilmodus- og Effektanalyse (FMEA) for et catenary fortøyningssystem for en Flytende Offshore Vindturbin (FOWT), er det nødvendig for rapporten å ha tilgjengelig historisk data for å støtte et solid grunnlag. Fra innsamling av informasjon og datainnsamling i de tidlige stadiene av oppgaven, lærte vi at det er lite til ingen spesifikk data som støtter oppgaven vår. Imidlertid brakte forskningen oss til de historiske dataene fra FPSO-er og semi-submersible olje- og gassriggers fortøyningssystemer. Fra et møte med MARIN [1], fikk vi bekreftelse på at fortøyningssystemene for FPSOer og FOWT er veldig like. Ved å undersøke de mange komponentene for både FPSO og FOWT, klarte vi å velge fem komponenter som var essensielle og vanligvis brukt for både FPSO og FOWT, se Figure 2-4. Det er noen forskjeller mellom de to som må adresseres. De tekniske forskjellene mellom en FPSO og en FOWT er betydelige, men samtidig ikke avgjørende for påstanden om at en FMEA for en FPSO ikke kan brukes for en FOWT. Forskjellene inkluderer forskjellige vanndyp og hydrodynamiske krefter, også kjent som vektfordeling og belastning. Siden FOWT er i tidlig utviklingsstadium, eksisterer det flere ukjente variabler. Materialene og komponentene operatører bruker i FOWTene sine varierer fra selskap til selskap. Å adressere dette, gjør det vanskelig for denne FMEA å være relevant, men det er viktig å merke seg at feilmodusene for en FPSO vil være de samme for en FOWT hvis komponentene er de samme. For eksempel vil en kjetting være den samme i begge tilfellene. Vi vet at catenary fortøyningssystemer er underlagt veldig forskjellige forhold. Likevel vil feilårsaken til slutt føre til de samme feilmodusene og profilene for hver komponent. For fremtidige anbefalinger og den mulige utviklingen av catenary fortøyningssystemer som brukes av FOWTer, har vi sett at erfaringen og den historiske integriteten til de fleste komponenter fra FPSOer er anvendelig for FOWTer med bevissthet om forskjellige miljøforhold. Denne FMEA kan være et grunnlag for fremtidig arbeid med fortøyningssystemet med riktig datasett og de nødvendige endringene med hensyn til de initielle forholdene, som belastning, miljø og driftsvariabler. Dette prosjektet har som mål å fullføre en sammenlignende studie mellom FPSOer og FOWTer og finne positive resultater, med fokus på overføring av kunnskap fra olje- og gassindustrien og dra nytte av erfaringer og lærdom. Med hensyn til drift og vedlikehold (O&M) av fortøyningssystemer for FOWTer, ser det ut til at komponenter som flytebøyer og klumpevekter kan føre til utfordringer. Mange komponenter av disse typene vil komplisere installasjoner, og i tilfelle de trenger utskifting, vil dette være enda mer komplisert.

Table of contents

1. Introduction

This chapter offers a comprehensive overview of the thesis, including relevant background information, clarification of the project's overarching aim, scope of work, potential limitations, and any relevant abbreviations.

1.1 Background

The future of Floating Offshore Wind Turbines (FOWT) is promising, and the development is accelerating. The world, mainly Europe, has an immense need for energy, and the floating wind turbine’s role is crucial for securing a new source of environmentally friendly energy. Offshore wind turbines will be installed at locations with less turbulence and higher wind speeds than onshore and, therefore, have a higher potential for energy production. With current technology, some locations with water depths over 70-80 m cannot be developed with bottom fixed turbines and will need reasonable solutions for floating wind turbines to harvest the wind energy. In Europe, four small floating wind farms are installed, totalling 176 MW of capacity. Two of these wind parks are Hywind Tampen and Scotland, the two only commercial wind parks exporting electricity for commercial usage worldwide as of 2024 [2]. The remaining wind turbines are referred to as test pilots in the industry. However, with the large-scale floating wind auctions expected in Spain, Portugal, France, the United Kingdom, and Norway, Europe is expected to have 3-4 GW of floating wind in operation by 2030. With the right policies by the government, Europe could potentially have 10 GW in operation by 2030 [2]. Politics has influenced the up-and-coming industry, whereas countries worldwide announce new fields operators can bid on.

Building on existing competence from the Oil and Gas (O&G) industry, the FOWTs have a vast potential for development. They could be a reliable option for new renewable energy. FOWTs consist of a wind turbine mounted on a floating platform connected to a mooring system configuration [3]. The purpose of a mooring system is to maintain the station and control the motions of the floating structure [4]. There are three main categories for mooring system design: catenary, taut, and Tension Leg Platform (TLP). This thesis will focus on a catenary-based mooring system, which is expected to be the most common and relevant for FOWT [5].

Over time, equipment, structures, and systems are degraded due to environmental and operational wear. Inspection and Maintenance (I&M) are therefore crucial to prevent potential failure of the mooring system. To develop a good I&M plan, the failure profile of equipment needs to be analysed using various types of data. The most used strategy is Reliability-centred Maintenance (RCM). In accordance with IEC 60300-3-1 [6], this is defined as method to identify and select failure management policies to achieve the required safety, availability, and economy of operation. An RCM includes Failure Modes and Effect Analysis (FMEA). FMEA is a method to identify potential failure modes, their causes, and their effects on system performance according to IEC 60812 [7]. As described in the Limitation, this report will only include FMEA.

1.2 Motivation

A FOWT needs a mooring system to maintain position and control the motion of the floating structure. The mooring system includes mooring lines and an anchor, where the anchor foundation's responsibility is to transmit forces from the FOWT to the seabed [3]. With time, the mooring line and anchor are subjected to environmental and operational wear, resulting in degradation. If left unattended, this degradation can result in structural deficiencies and, ultimately, failure. Hence, there is a need to systematically study the existing mooring system to identify the modes and mechanisms by which the individual components of the mooring system may fail. The knowledge would help develop a better I&M plan for the mooring system. The optimized I&M plan is expected to help the wind farm operator save a substantial number of resources in the future. For offshore Wind Turbine Generators (WTG), costs related to downtime can be more significant than those onshore. Suitable weather windows are required for corrective maintenance. For instance, during wintertime, when winds are high, significant energy production is lost when waiting for calm weather windows to conduct a repair.

1.3 Aim of Project

The project aims to study failure profiles for the Catenary Mooring System of a Semi-Submersible Floating Offshore Wind Turbine (FOWT) based on experience from a Floating Production, Storage, and Offloading (FPSO) Vessel.

1.4 Scope of Work

The Scope of work Includes:

1. Description of FOWTs, FPSOs, and Structure Design of Catenary Mooring Systems on Semi-submersible FOWTs.
2. Description of Failure Mode and Effect Analysis (FMEA) Techniques based on relevant IEC, DNV, and ISO standards.
3. Carry out an FMEA for Catenary Mooring Systems on FPSO.
4. Present FMEA of Catenary Mooring Systems on FPSO.
5. Make an overview of recommendations for future work and direction.

1.5 Limitation

Due to minimal experience in the operations of full-scale FOWT wind farms, there is a lack of documentation and historical data related to mooring systems on FOWTs. Therefore, an FMEA for an FPSO is used as a basis and adopted for wind farms consisting of FOWTs. The RCM method will be constrained to study preparation, system selection & definition, FFA, leading to a final FMEA. This limitation is primarily due to data availability and time constraints. This paper will focus on the most field-reliable and common types of mooring systems and equipment and, therefore, is limited to catenary-based mooring systems and Drag Embedded Anchors (DEA), excluding any concept designs.

1.6 Structure

This thesis is divided into seven chapters.

- Chapter 1. Introduction – The introduction presents the background and motivation for the project, scope of work, limitations, structure, and abbreviations.
- Chapter 2. Literature Review – The chapter provides an overview of FOWT and FPSO, the comparison between them, and the structural design of the catenary mooring system. It goes in-depth on mooring lines, mooring connectors, mooring anchors, subsurface buoys, and clump weights.
- Chapter 3. Methods and Approach – Methodology explains how the analysis is carried out, including what methods and tools are used. It covers the underlying philosophy behind the study.
- Chapter 4. Results and Discussion – Results and discussion present the FFA and FMEA.
- Chapter 5. Future Directions and Recommendations – Provides recommendations and directions for future work based on this thesis.
- Chapter 6. Conclusion – Conclusion.
- Chapter 7. References – References.

1.7 Abbreviations

AHV	Anchor-Handling Vessel
DEA	Drag Embedded Anchor
DNV	Det Norske Veritas
DP	Dynamic Positioning
FFA	Function Failure Analysis
FMEA	Failure Mode and Effect Analysis
FOWT	Floating Offshore Wind Turbine
FPSO	Floating Production Storage and Offloading
HMPE	High-Modulus Polyethylene
IEC	International Electrotechnical Commission
I&M	Inspection and Maintenance
ISO	International Standards Organization
IWRC	Independent Wire Rope Core
JIP	Joint Industry Project
O&G	Oil and Gas
O&M	Operation and Maintenance
OPB	Out of Plane Bending
OTC	Offshore Technology Conference
MBL	Minimum Breakage Load
MIC	Microbially Induced Corrosion
MODU	Mobile Offshore Drilling Unit
SRB	Sulphate Reducing Bacteria
STL	Submerged Turret Loading
TDP	Touch Down Point
TLP	Tension Leg Platform
ULS	Ultimate Limit State
WTG	Wind Turbine Generator

2. Literature Review

It is essential to understand FOWTs and O&G installations to understand the vitality of mooring systems. O&G installations must stay in a location to avoid damage to critical equipment such as risers and drill strings. In contrast, FOWTs must stay on location to avoid impacts against neighbouring WTGs and ensure optimal wind production. The main function of a mooring system is to keep a structure at a specific location, which is typical for both O&G rigs and FOWTs. This chapter will, therefore, include a general overview of FOWTs and O&G Rigs. The literature review also describes mooring systems, components, functions, and failure mechanisms. This is crucial for further understanding and identifying potential failure modes of each component.

2.1 Overview of FOWTs

FOWTs harness wind energy to generate electricity. FOWTs are mounted on floating structures anchored to the seabed. This distinction allows for deployment in deeper waters, minimizing visual impact from the coast and taking advantage of more consistent and stronger winds. Consequently, FOWTs offer increased efficiency in electricity production. FOWTs also offer logistical advantages. They can be assembled at port facilities before transportation to deployment sites, streamlining installation processes. The ability to bring turbines ashore for extensive maintenance or decommissioning enhances operational flexibility and maintenance logistics. FOWTs consist of three main parts: a wind turbine mounted on a floating platform, connected to a mooring system configuration [2]. Each part serves a different role on the FOWT. The wind turbine converts wind to electrical energy, the floating platform ensures buoyancy, and the mooring system controls the motions of the floating structure and maintains its position [8]. FOWTs are still in early development, and only a few FOWTs have been operating as of April 2024. Because of the early-stage development, different concepts of FOWTs are designed, tested, and used. There are many concept ideas for floaters, three of the promising concepts are TLP, spar platform, and semi-submersible platform.

Figure 2-1. FOWT semi-submersible concept Equinor Scotland [45].

2.2 Overview of FPSOs

An FPSO vessel is a versatile offshore platform used in the O&G industry to extract, process, and store oil and gas.

FPSOs serve as Mobile Offshore Production Units (MODU), particularly in remote or deepwater O&G fields where traditional fixed platforms are not feasible. They enable the production of O&G directly at the offshore site, reducing the need for costly subsea infrastructure and long-distance pipelines [9]. FPSOs typically comprise a converted tanker with topside processing facilities, storage tanks, and a mooring system. The topside facilities include equipment for crude O&G processing, water treatment, and power generation [10]. Depending on the water depth and environmental conditions, FPSOs are anchored to the seabed using a spread mooring or Dynamic Positioning (DP) system. They receive O&G from subsea wells through risers and pipelines, and process onboard. FPSOs have onboard storage tanks to store processed crude oil until offloaded onto shuttle tankers or export pipelines for transportation to refineries. They can also store produced water and associated gas for re-injection or offloading. One of the critical advantages of FPSOs is their flexibility and mobility. They can be easily redeployed to new fields or locations as production declines or new opportunities arise. This flexibility makes FPSOs cost-effective for offshore O&G production in diverse geographical and operational conditions. FPSOs are subject to strict safety and environmental regulations to protect personnel and the environment. They have advanced monitoring, control, and safety systems to reduce operational risks. FPSOs have a long operational lifecycle of 20-30 years, with periodic maintenance, upgrades, and refurbishments to extend their service life [11].

Figure 2-2. Johan Castberg FPSO accessed from Teknisk Ukeblad [46].

2.3 Comparison between FOWTs and FPSOs

This chapter compares FPSO and FOWT and reviews the slight differences that must be considered when making an FMEA for FOWTs based on the experience drawn from FPSOs. Firstly, the number of mooring lines differs between FPSOs and FOWTs. A FOWT usually has 3-4 mooring lines [12] while an FPSO has, on average, 8-12 mooring lines [13]. The dissimilar number of lines is due to cost and safety. For an FPSO, the criticality of a line breakage is more severe than that of an FOWT [14]. In the case of mooring line failure, the FPSO can lose its station-keeping ability, which can damage risers, riser hang-ups, or seabed facilities. Such damage can harm the environment and personnel due to oil spills and gas explosions [14]. Conversely, a FOWT will only drift away, tilt, or break, leading to a lesser environmental impact than an FPSO. The number of lines is also correlated to weight. The fact that the FOWTs are generally much slimmer than an FPSO around the waterline also contributes to a more significant wave drift force than the FPSO and, consequently, the need for increased mooring strength. For example, the Hywind Tampen FOWTs will be around 10m wide in the water line, while the new Johan Castberg FPSO will be 55m wide [15].

There are some variations in the selection of different types of mooring lines. FOWTs typically use synthetic fibre mooring lines to provide flexibility and reduce weight. FPSOs often use steel wire rope, due to higher loads on the lines. The variations in the selection of lines are constantly developing, and most offshore floaters utilize a combination of wire rope, chains, and synthetic lines.

As mentioned, the FPSO has twice the weight dispersion of a FOWT. The FOWT is lighter and relatively smaller, and its overall weight needs to be minimized to increase the efficiency of turbine operations. The FPSO is heavier and more prominent due to its storage of oil and gas and the processing equipment used onboard.

As of 2024, most FOWTs are designed for moderate water depths up to 200 meters; as technology advances, deeper deployments are considered feasible [5]. FPSOs can operate in a wide range of water depths, from shallow to extreme depths. In a few years, the Raia field in Brazil will be in production using an FPSO at 2900m depth [16]. This makes the FPSO versatile for extracting oil and gas worldwide [9].

FOWTs are intended to be deployed in arrays or grids on a wind farm with multiple turbine units, consists of any number from 5 to 100 units. This aspect needs to be addressed when developing I&M plans for FOWTs. FPSOs are deployed as singular units, which reduces the cost of inspections by allowing various monitoring and inspection methods to be applied more affordably. This is especially crucial given that downtime for an FPSO is more critical [1].

In the FOWT industry, several concepts are available and constantly evolving. These concepts implicate different types of mooring systems, components, stability, cost, and ease of deployment that may affect an inspection plan. These concepts include semi-submersible, spar, barge, and TLP, which are the most common concepts developed [17]. FPSOs are well-known ship-shaped hull designs that have been field-proven for several years in operations and are tailored to the conditions and operational requirements [10].

The most vital aspect of comparing a FOWT and FPSO is the selection of components. FPSOs and FOWTs utilize the same mooring lines, anchors, cables, and connectors for mooring segments. Note that adaptations must be made to operational requirements.

The layout of mooring lines can vary for the FOWT structure, ranging from plain catenary to taut, shown in Figure 2-3. Depending on height, turbine size, water depth, and additional conditions, the catenary mooring line can be up to 2500 meters [14]. This is because it needs the weight and length to support the geometric stiffness of the catenary shape of the mooring line.

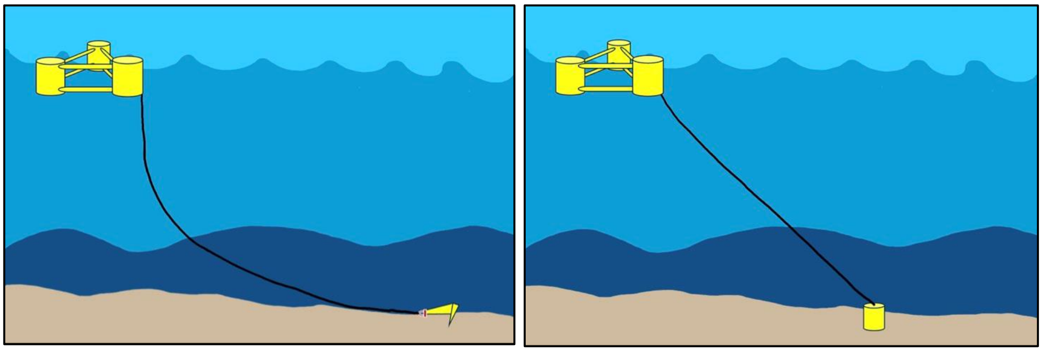

Figure 2-3. Illustration by T. Ågotnes based on general information in the open domain on catenary mooring line (left) and taut mooring line (right).

The lifecycle of FPSOs and FOWTs is similar and designed for extended operations of 20-30 years. FPSOs are field-proven and provide existing technology and experience that is required to keep it operating for 30 years. Therefore, is it safe to assume that the experience needed to keep an FPSO operating for 30 years is also relevant for a FOWT.

2.4 Catenary Mooring Systems: Components and Function

The mooring system of a floating unit, FPSOs and FOWTs, can be divided into two main areas of interest. These are the components of the mooring system and the configuration, which is how the operators choose to apply the mooring lines to the floating unit.

The different configurations use different combinations of components depending on environmental and geological conditions. The components in a mooring system can be divided into these main categories:

- Mooring Lines
- Mooring Connectors
- Mooring Anchors
- Subsurface Buoys
- Clump Weights

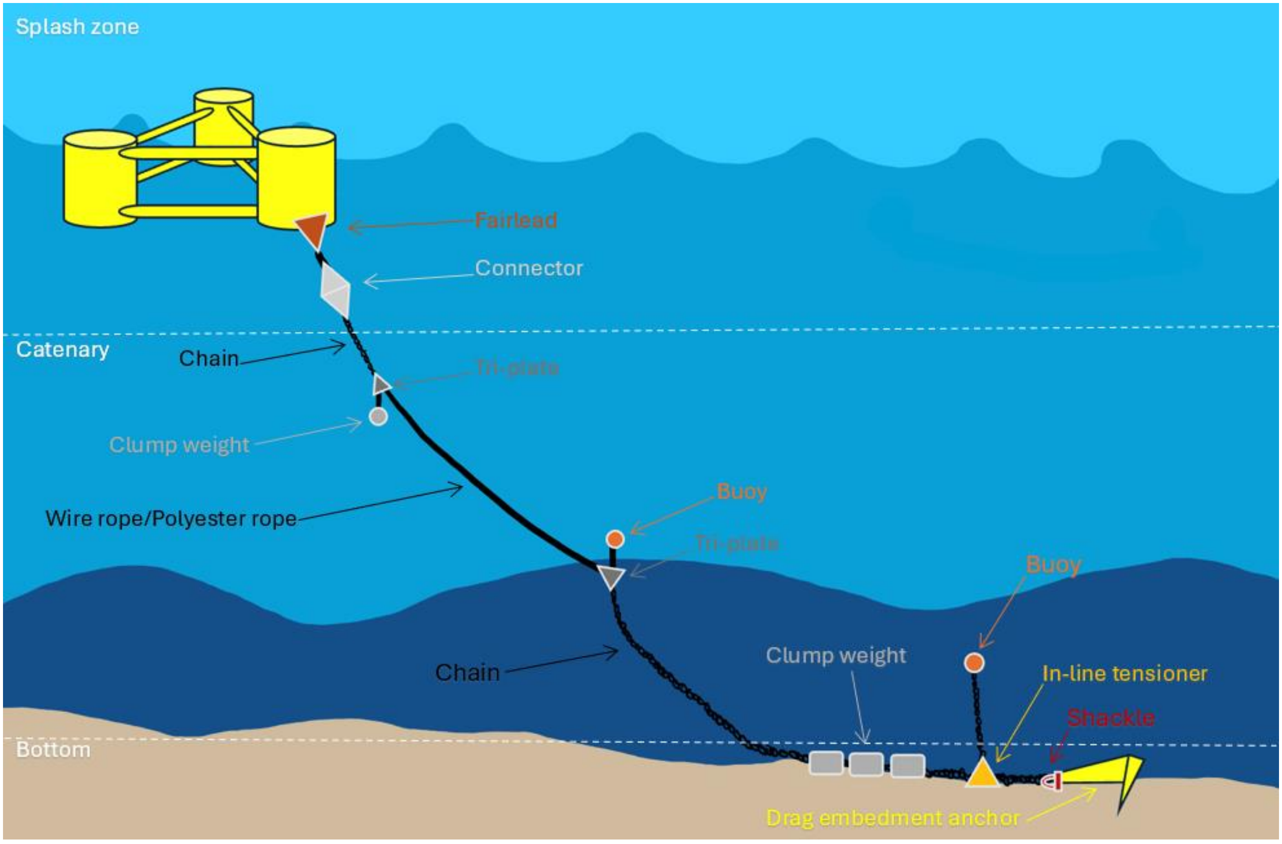

Figure 2-4. Illustration by T. Ågotnes based on general information in the open domain on mooring systems.

2.4.1 Mooring Lines

The mooring lines connect to the floater through fairleads and to the seabed through anchors. The mooring lines are typically seen with a combination of materials such as wire, synthetic fibre ropes and steel chain links.

Chains

The chain link's main purpose in the mooring system is to provide weight, stability, and absorbing forces [18]. Offshore Mooring chains, according to DNV-OS-E302 [19], are classified into six different quality grades, ranging from R3, R3S, R4, R4S, R5, and R6. These quality grades are derived from the Minimum Breaking Load (MBL). When a chain is utilized in water depths greater than 300 m, the weight of the chains will cause the catenary shape to drop, increasing the angle between the seabed and the vertical line from the floater. This reduces the catenary effect and the mooring line’s ability to absorb the forces from the floater.

Wire Rope

The wire in offshore mooring systems plays a critical role in anchoring offshore structures securely, transmitting loads, providing flexibility, and ensuring the durability of the entire mooring system in challenging marine conditions. A wire rope consists of several smaller steel strings, and the two significant types of wire rope used in mooring systems are six-strand wire and spiral strand wire, shown in Figure 2-5. The six-strand wire is mainly used in MODUs due to its flexibility. The six-strand is shaped like a helix, creating torque as tension increases [20]. The six-strands are again divided into Independent Wire Rope Core (IWRC) classes depending on the number of strands in the wire. For example, 6x36 contains six-strands with 36 minor strands within the 6 strands.

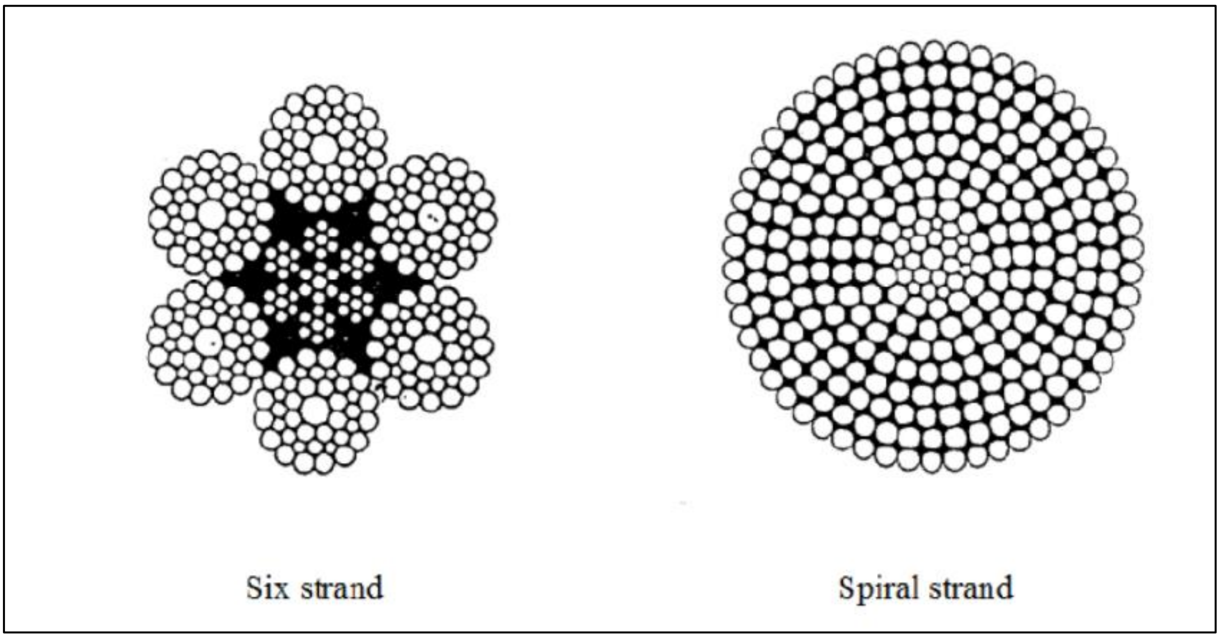

Figure 2-5. Illustration on Six-Strand and Spiral-Strand rope [20].

The spiral strand shown in Figure 2-5 contains several strands layered on each other, alternating in different directions, creating a good torque balance. The wire rope used in offshore mooring systems should be applied and manufactured according to DNVGL-OS-E304 [20].

Synthetic Rope

Synthetic fibre ropes serve as an intermediary section connecting sections at the top and bottom of the mooring line through connectors. The synthetic section is light compared to chains, and when the load is inflicted, the synthetic fibre rope stretches [14]. Synthetic mooring ropes are manufactured from various types of synthetic materials. The most common are High-Modulus Polyethylene (HMPE), nylon and polyester [21]. Synthetic ropes used in mooring systems should be manufactured according to DNVGL-OS-E301 *Position Mooring* [22], DNVGL-OS-E303 *Offshore Fiber Ropes* [23] and DNV-RP-E305 [21]. The components of the fibre rope are shown in Figure 2-6.

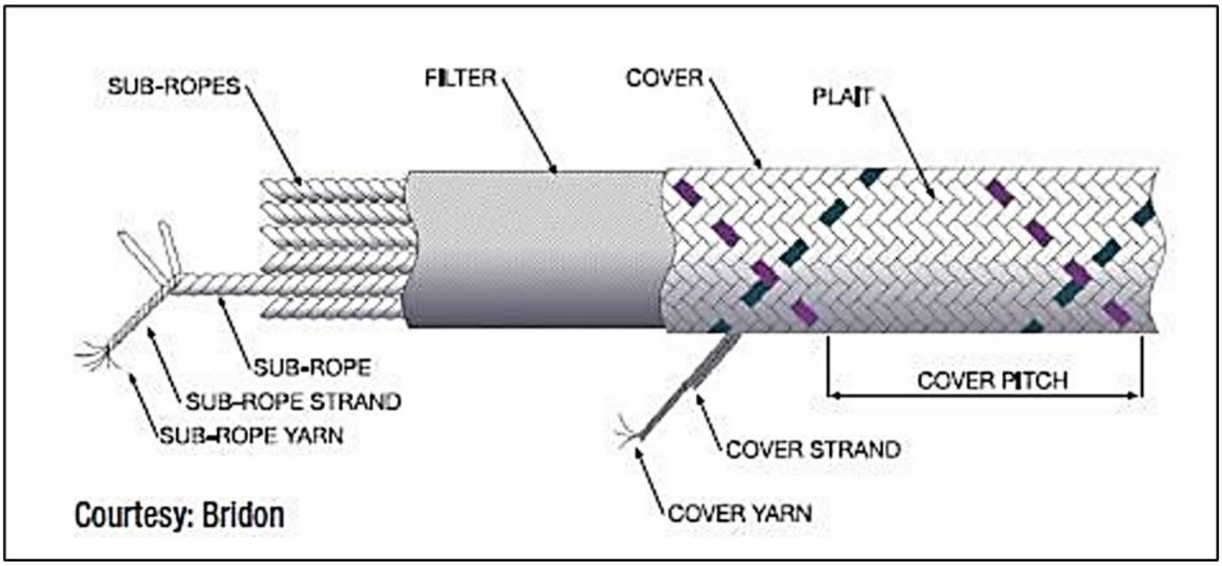

Figure 2-6. Illustration of a synthetic rope [24].

2.4.2 Mooring Connectors

Mooring connectors connect components in the mooring line and are used in connection points, such as between the floater and the mooring line. For this thesis, the selected connectors investigated in the FMEA analysis are Fairlead, H-links, Tri-plates, In-Line Tensioner and Shackles.

Fairlead

Fairleads guides the mooring lines, enabling the mooring line to secure its way from the sea up onto the floater. Its primary purpose is to securely change the chain's direction without the risk of getting stuck or chafing. An illustration of the fairlead is shown in Figure 2-7.

Fairleads are installed on various O&G installations, such as the Goliat FPSO and Hywind Tampen. MACGREGOR produces fairleads for the O&G industry and new FOWTs. Therefore, it is proven that the experience from O&G is transferrable to the FOWTs industry [14, 25].

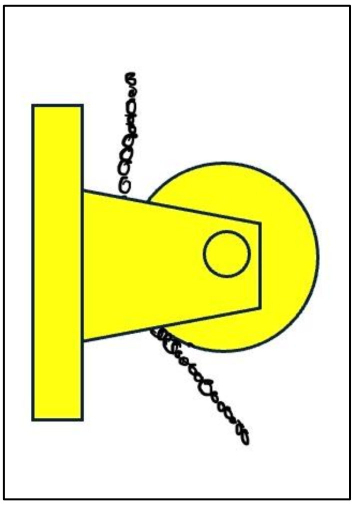

Figure 2-7. Illustration by T. Ågotnes based on general information in the open domain on Fairlead.

H-links

H-link is a solid connector that is suitable for various equipment. It can be used as a universal connector to adjust the mooring lines length. The H-link's main objective is to connect chains with the same diameter or different explicitly suited for the H-link. It connects padeyes, closed and open wire rope sockets, and synthetic rope thimbles. Note that every company has a slightly different design for its H-link, but the principles are the same overall [26].

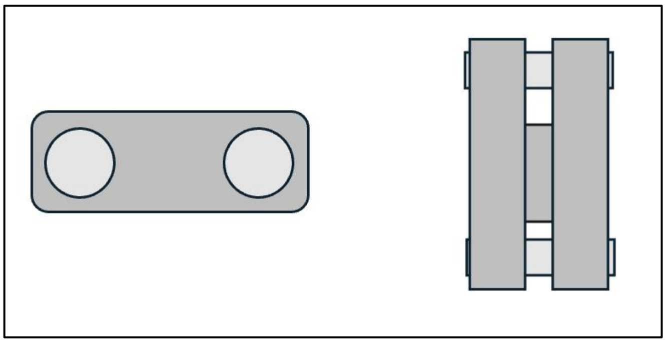

Figure 2-8. Illustration by T. Ågotnes based on general information in the open domain on H-Link.

Tri-plate

A tri-plate is a triangular connection point. The tri-plate allows for multiple attachments. The tri-plate secures efficient load distribution and aids in avoiding concentrated stress points. Tri-plates in FOWT mooring systems often attach accessories such as clump weights or subsurface buoys to the mooring line [27].

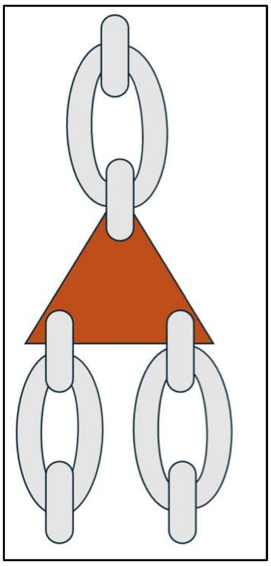

Figure 2-9. Illustration by T. Ågotnes based on general information in the open domain on Triplate.

In-Line Tensioner

The in-line tensioner is a device that gives access to the mooring line from Anchor-Handling Vessel (AHV). The objective is to adjust and regulate the tension in mooring lines to ensure the stability and safety of offshore installations. In-line tensioners are typically installed within the mooring line, allowing for continuous tension adjustment without disconnecting the line. They are usually positioned along the length of the mooring line at strategic points where tension adjustments are required. In-line tensioners feature mechanisms that allow operators to increase or decrease the tension in the mooring line as needed. This adjustment capability is crucial for accommodating changes in environmental conditions such as wave height, wind speed, and tidal forces. Some in-line tensioners may also be equipped with monitoring systems that provide real-time data on the tension levels in the mooring lines. This data helps operators make informed decisions about tension adjustments and ensures that mooring lines remain within safe operating limits. In-line tensioners enhance safety during mooring operations by providing a controlled method for adjusting tension without requiring manual handling of heavy mooring lines. They also help prevent the overloading of mooring lines, which can lead to structural damage or failure of offshore installations [28].

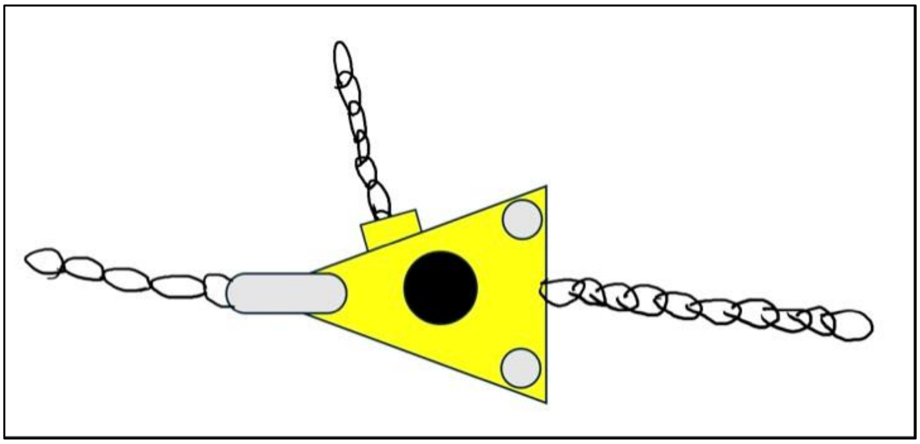

Figure 2-10. Illustration by T. Ågotnes based on general information in the open domain on In-Line Tensioner.

Shackles

Shackles are a simple component used in most construction industries and transportation. Its purpose is to interlock heavy objects, often seen between chains and equipment, such as anchors. The shackle comes in various sizes depending on the load capacity it is meant to bear. The shackle is made from stainless or galvanized steel to endure the rough marine environment [29].

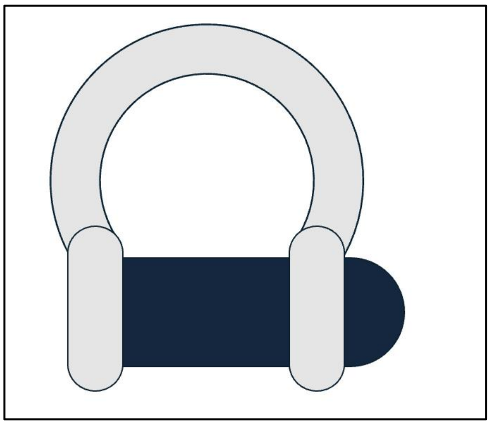

Figure 2-11. Illustration by T. Ågotnes based on general information in the open domain on Shackles.

2.4.3 Mooring Anchors

Depending on the geological conditions, there are several different options when it comes to anchors, see Table 1. The selection of the anchor type must be compatible with the configuration of the mooring lines. The existing concepts of FOWTs utilized either suction piles or DEA [5]. The seabed on the Norwegian continental shelf mainly consists of clay well suited for DEA [30]. For the FMEA analysis, the DEA is selected [27].

Table 1 – Descriptions of Anchors [14, 31]

Anchor Type	**Advantages**	**Disadvantages**
Drag	• Fast Installation • Easy fabrication • Used By FOWTs • Suitable for Catenary • Well Suited for Clay soil	• Low resistance to vertical loading. • Horizontal Loading only
Suction	• Shared Anchor system proven. • Used by FOWTs • Both horizontal and vertical loading	• Unsuitable for high-strength soil • Potential scour development
Driven Piles	• Potentially shared Anchor system • Precise location • Good for vertical loading • No creep	• Time-consuming • Difficult to remove. • High cost
Drilled & Grouted	• Potentially shared anchor system • Reliable • High Vertical loads	• Time-consuming • Expensive
Torpedo	• High vertical load • Precise location • Not likely to creep	• Not suitable for soft soil • Limited experience
Gravity	• Good for TLP • Both horizontal and vertical Loading	• Extremely large and heavy • Needs a lot of materials

Drag Embed Anchors (DEA)

DEAs are anchors dug deep within the seabed, gaining their loading capacity from the weight of the seabed surrounding it. They are installed by being dragged into the seabed using a mooring chain and an in-line tensioner, see Figure 2-10. Their efficiency is due to their concentrated mass deep within the seabed, where soil resistance is most significant. As mentioned previously in this report, DEAs are designed to resist horizontal forces only, making them suitable for catenary-moored configurations. Catenary mooring lines exert only horizontal forces on the anchors, while taut mooring lines exert horizontal and vertical forces. A DEA consists of a shank, a fluke, and a padeye [5]. The shank is the main body, transporting weight loads from the fluke to the mooring line. The shank is designed to glide effortlessly through the seabed with little resistance. The fluke is the bottom part of the anchor and is designed to be a blade digging deep down into the seabed. It is responsible for the anchor's holding capacity [32] see Figure 2-12.

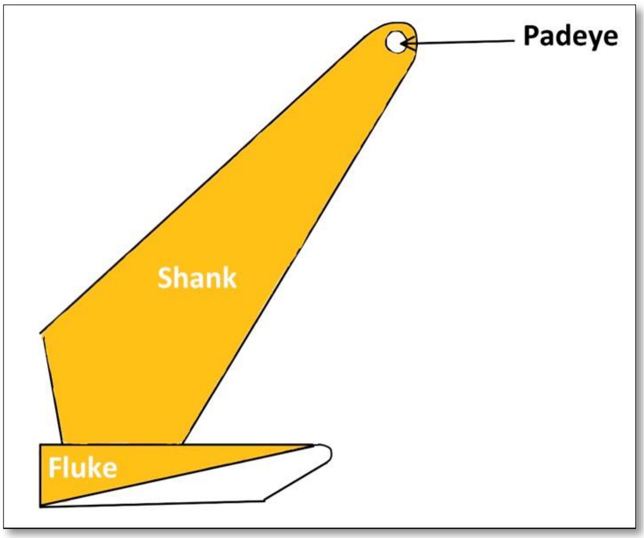

Figure 2-12. Illustration by T. Ågotnes based on general information in the open domain on DEA.

2.4.4 Subsurface Buoys

In different types of mooring configurations, the buoys are an addition to prevent damage to wire rope. Submerged buoys elevate sections of the mooring line from the seabed, thereby diminishing the likelihood of failure. This is primarily due to reduced wear and tear caused by the line rubbing against the seabed and a lower risk of soil particles infiltrating synthetic lines, which could degrade the integrity of the line. Subsurface buoys are often combined with clump weights in shallow waters up to depths of 200m [14]. Subsurface buoys in O&G are most used by FPSO in Submerged Turret Loading (STL) systems [12]. Since subsurface buoys are used in FPSO, experience and knowledge from the O&G industry can be applied to FOWTs. Subsurface buoys alter the horizontal forces in the mooring line system and, therefore, might work well with the catenary system used by FOWTs in the Norwegian Sea [5, 12].

2.4.5 Clump Weights

Clump weights are a new addition to the Mooring systems and aim to improve mooring performance by adding weights to specific points to reduce loads [33]. Their main function is to counteract the buoyancy and dynamic forces acting on offshore structures, maintain their position, and prevent excessive movement or displacement. Clump weights are typically composed of concrete or steel. Clump weights are strategically placed and attached to the mooring line or using tri-plates in the upper section of the mooring line.

2.5 Failure Modes and Profiles in Mooring Systems

This chapter is based on the Offshore Technology Conference (OTC) papers ; *A Historical Review on Integrity Issues of Permanent Mooring Systems* [34] , *Mooring Integrity Issues and Lessons Learned Database* [35] and *Floating Production Mooring Integrity JIP-Key Findings* [36]. These papers study failure profiles for FPSOs. Due to a lack of historical data for FOWTs, utilizing data from FPSOs is crucial to discovering potential failures that may occur in a mooring system for FOWTs. Based on the assumption that the components in FPSO and FOWT mooring systems are the same, they are expected to suffer from similar hazards. This chapter reviews the common failure profiles in the referenced OTC papers and their connection to FOWT mooring systems.

2.5.1 Fatigue

Fatigue is a standard failure mode in the O&G industry, and chains are frequently exposed to fatigue over time. Fatigue can arise from several different causes, referred to as failure causes. Failure causes related to fatigue are load cycles, flawed flash welding, operation exposure, hydrogen-assisted cracking, and design flaws. These failures lead to reduced strength on the surface area of the chain link, which again creates cracks on the surface, typically in the crown of the chain link. If the cracks grow without proper I&M, they will eventually break. Note that this happens over a very long period. The paper *Mooring integrity issues and lessons learned Deepstar database project* [35] investigated the integrity of the mooring line over 10 years with several different types of FPSOs. The experiences from FPSOs are considered relevant also for the FOWTs and used in the FMEA described in chapter 4.2 in this report.

2.5.2 Corrosion

Corrosion is one of the main contributing factors to the degradation of components. A corrosion process is when a metal is transformed into a chemically stable form, like oxide or sulphide. Corrosion is the decomposition of materials due to electrochemical reactions with the environment. The corrosion process will usually cause weakening of the material strength and can potentially result in failure or collapse of the corroded material. The marine environment surrounding the mooring system offers good conditions to start a corrosion process [37].

2.5.3 Wear

Wear and tear of the subsea components is due to the degradation of the materials over time. Out-of-plane bending (OPB) is a case of wear observed in O&G mooring systems. The OTC papers *Historical Review on Integrity of Permanent Mooring Systems* [34] and *Mooring Integrity Issues and Lessons Learned Data Base from the Deepstar Project* [35] both refer to the failure mode “out of plane bending” and describes this as a well-known failure associated with chain links. When the floater moves out of position, or chains tangle, friction-induced bending is created. Friction-induced bending is the root cause of OPB and causes friction and tear in the crown section of the chain link. This leads to interlock rotation of the chain segments, and the tension between the chain links increases until the chain snaps. Load cycles are also a cause for wear and are cohesive with OPB [38]. When the floater moves, the chain links stretch and contract to align with the floater’s movement, which creates wear inside the interlock section in the crown of the chain. This reduces the crown's overall surface strength and degrades the chain link. Marine growth is also considered when discussing the wear and tear of mooring systems. Marine growth refers to environmental and biological conditions such as barnacles, kelp, and algae. These environmental issues can further contribute to the degradation of the mooring system. Marine growth can add weight or disturb the balance of the mooring system and produce unwanted drag forces.

2.5.4 Corrosion fatigue

Sulphate-Reducing Bacteria (SRB), exist in harsh marine environments on the sea floor and cause corrosion of iron, which is often utilized in chain links. SRB lives on minerals and produces hydrogen sulphide when in contact with iron and steel. The sulphide acid causes corrosion of the chain. SRB is often the primary type of Microbially Induced Corrosion (MIC) seen in mooring systems. MIC is an electrochemical type that often leads to pitting, cracking, or galvanic corrosion. MIC alters the material's surface to initiate corrosion. Microorganisms either change the surface of the chain link physically or alter the chemical conditions of the metal. MIC often appears as a uniform corrosion; in most cases, it leads to pitting in the chain link’s crown surface. In the FMEA, the cause of MIC is called environmental exposure due to the metal's contact with the surrounding marine environment containing these microorganisms. This, again, leads to the oxidation of the metal of the chain links [39].

2.5.5 Mechanical Failure

A mechanical failure in an offshore mooring system refers to any malfunction, damage, or breakdown of mechanical components within the mooring system that compromises its ability to effectively secure and stabilize offshore structures such as oil rigs, floating production platforms, or vessels.

2.5.6 External Damage

External damage or abrasions often occur around the touchdown point of the mooring line. When the mooring line goes from its catenary shape to horizontal, the arch hits the seabed repeatedly when the floater moves, creating abrasions or impact forces typical on the chain section of the mooring line. These impact forces create fractures in the mooring chains' surface, reducing surface strength and possible cracks that might support a corrosion cycle [14].

2.5.7 Overload

Overload is a failure associated with extreme loads, often beyond the Ultimate Limit State (ULS). Overload often appears when storm loads or hurricanes with return periods longer than 100 years for oil and gas installations or longer than 50 years for wind turbines, hit the floater and create excessive tension on the mooring system, creating cracks in the chain segments. When these cracks appear, they give a foundation for bacteria and corrosion, increasing the degradation rate of the chains.

2.5.8 Manufacturing Defect

Manufacturing defects are not likely to appear since they must go through certification to be applied offshore, but mistakes happen. Manufacturing defects can include flaws in design and welding, which can create weak spots on the surface.

2.5.9 Installation issue

Installation issues are failures associated with incidents onboard the responsible vessel before the mooring line is installed in the mooring line system. These issues include impact forces, wrong handling, and poor flash welding. They can create small cracks and weak points in the mooring line section that align with manufacturing defects. These weak points increase the degradation rate of the chain links and depending on the severity of the incident onboard the AHV, it can take weeks or years to discover.

3. Methods and Approach

In this chapter, the methods used to complete the assignment are described.

3.1 Methods

This thesis is based on qualitative and quantitative methods for gathering data. The qualitative method employed in this study revolves around the collection of information and the execution of personal evaluations. Analytical tools such as Functional Failure Analysis (FFA) rely on the expertise of individuals. When assessing failure modes, using this approach is crucial, as the outcomes can differ depending on the individual's experience level.

In contrast, quantitative methods rely heavily on statistical data and information. This entails gathering malfunction data from components and past failure modes. However, this thesis will not delve into quantitative analysis. Due to time limitations and lack of publicly available historical data on failure modes, a risk analysis in the FMEA will not be executed [40].

3.2 Structuring the FMEA

The excel spreadsheet utilized in this analysis draws inspiration from Professor Maneesh Singh, an Operations and Maintenance Engineering expert at HVL. Professor Singh provided a spreadsheet derived from a risk matrix developed by DNV, which was further refined and developed over years of practical experience.

3.3 FMEA

FMEA is an abbreviation for Failure Mode and Effect Analysis and is the most used failure mode analysis in the wind turbine industry. FMEA involves linking failure modes, their impacts on system performance, and underlying causes. There are multiple standards for applying an FMEA, depending on the company, region, purpose, etc. However, in most cases, an excel spreadsheet template will be used to list every part of the system in interest and analyse each. This usually requires a technical hierarchy where several parts comprise one subsystem, further making one system [41].

FMEA demonstrates its utmost value when applied actively during the design phase, allowing for continual improvement and reliability checks. Users of this analysis must be mindful of potential cascading effects, where a failure in one component triggers hazards in another. To effectively manage this, FMEA focuses on immediate impacts without delving into downstream consequences. It is crucial to maintain a stepwise approach, analysing each part's hazards and failure mode without extending too far into future scenarios. This approach prevents overcomplication and ensures manageable risk assessment [42]. Before starting on the creation of a comprehensive FMEA spreadsheet, several preparatory phases are crucial. Understanding the system, its subsystems, and individual components allocated to the FMEA is essential. This requires an in-depth study preparation. Once an understanding of the system is acquired, a selection and definition of the subcomponent and analysis are necessary. Subsequently, a FFA for each chosen subcomponent is vital. These preparatory steps are essential to complete an FMEA. The outlined steps in the FMEA spreadsheet are described in FMEA Definitions.

3.3.1 Study Preparation

Preparation for the study includes gathering information, defining the scope of the assignment, and establishing limitations. This process involves delving into industry standards and different approaches to FMEA, obtaining detailed information about the Catenary Mooring System, and providing an overview of FOWTs and FPSO. These preparations help establish a robust foundation for the study, ensuring comprehensive coverage and a methodical approach to the subject matter.

3.3.2 System Selection & Definition

Before initiating an FMEA analysis, it is essential to identify the system where the FMEA will be beneficial and determine the appropriate assembly level (system, subsystem, component) for conducting the analysis. To establish a technical hierarchy, reference can be made to Marvin Rausand’s framework, which outlines four levels [43].

Plant – Encompasses a collection of systems functioning cohesively to generate specific outputs.

System – Comprises interrelated subsystems dedicated to fulfilling a primary function within the plant.

Sub-System – Constitutes a smaller unit within a more extensive system capable of autonomous operation.

Maintainable Item – Refers to a component capable of independently performing a significant function.

Figure 3-1 and Figure 3-2 illustrates Rausand’s framework applied on an FPSO with the purpose to identify failure modes in the mooring system.

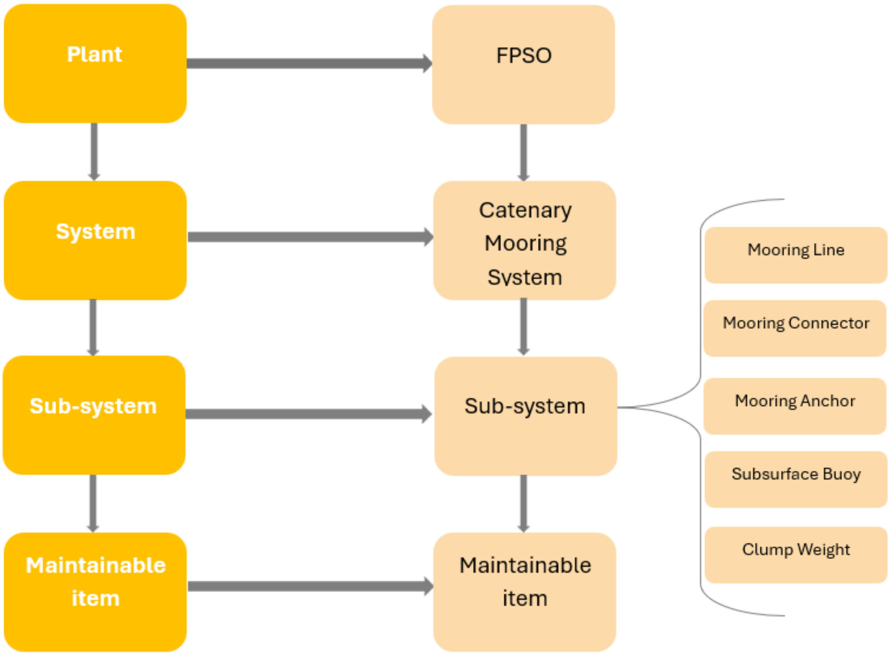

Figure 3-2. Technical Hierarchy illustrated by T. Ågotnes.

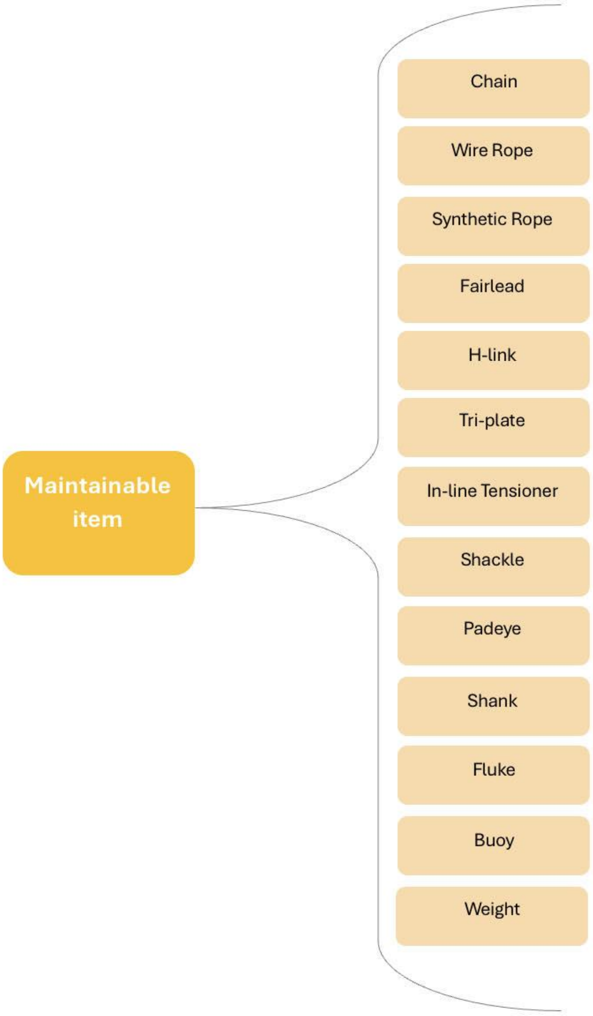

Figure 3-1 Maintainable Item illustrated by T. Ågotnes.

3.3.3 FFA

FFA thoroughly outlines each maintainable item's function and potential failure in the catenary mooring system. Each item’s function is segmented into two categories: the main function, which is a function unrelated to or indirectly part of the function for another component, and the secondary function, which is a function that is related to, but not directly, part of the main function of the component [44]. Function failure is categorized into main function failure, which is the failure of a component not directly or indirectly caused by another component's failure or fault, and secondary function failure, which is the failure of a component caused directly or indirectly by another component's failure or fault [44].

After selecting a specific system in “*System Selection and Definition*”, 3 steps in the FFA are performed:

1. Identifying and describing the system's required functions and performance criteria,
2. Describing input interfaces needed for the system to operate, and
3. Identifying potential ways in which the system might fail to function.

1. Identification of System Function

The system usually has a higher number of different functions. In identifying the various functions of a system, it is crucial to cover a range of categories. Functions can be categorized into 8 different functions:

Essential functions – are those necessary for the item's intended purpose.

Auxiliary functions – support the essential tasks.

Protective functions aim to safeguard people, equipment, and the environment, such as safety valves on pressure vessels.

Information functions – encompass condition monitoring and alarms.

Interface functions – defines interactions with other items, whether active or passive.

Equipment modifications or overspecification may create redundant functions. These functions may not align with the system's actual operational context and could cause other functions to fail.

Online functions are based on operation frequency; they occur so often that the user has current knowledge about their state or continuously.

Off-line functions are based on operation in frequency; they occur rarely, and the user does not know their availability.

This classification serves as a checklist to ensure all essential functions are identified without engaging in debates over classification terms like "essential" or "auxiliary." Systems may operate in various modes, each with its functions [43].

2. Identification of Interfaces

System functions can be mapped out using tools like functional block diagrams, providing a clear understanding of how inputs interact with functions. For more detailed analysis, breaking down system functions into subfunctions is possible through reliability block diagrams and fault trees [43].

3. Functional Failure

This phase involves conducting an FFA to identify system failure modes. Various classification schemes ensure a thorough identification process, encompassing categorizations like sudden or gradual failures, with a focus on aging failures. Using a structured spreadsheet as an FMEA helps organize critical information such as operational modes, system functions, performance criteria, and identified failures are documented [43].

3.3.4 FMEA Definitions

Table 2 - FFA and Failure Profile description

Function Failure Analysis	Equipment Failure Profile
System: Explains which system the equipment is a part of. In this case, the system will always be a catenary mooring system. **Equipment:** This refers to the equipment in the selected system that is further investigated. In the catenary mooring system, five main pieces of equipment are in focus: the mooring line, mooring connectors, anchor, subsurface buoy, and clump weight. **Maintainable Item**: Specifies the component's name to which the identified failure mode belongs. **Primary Function:** A function unrelated to or indirectly part of the function for another component. **Main Function Failure:** Failure of a component not directly or indirectly caused by another component's failure or fault. **Secondary Function**: A function that is related to, but not directly, part of the main function of the component. **Secondary Function Failure:** Failure of a component caused directly or indirectly by another component's failure or fault.	**Hazard:** Which danger or risk comes from the function failure? **Hazardous Event:** How the hazard from function failure occurs. **Failure Cause:** Circumstances during specification, design, manufacture, installation, use, or maintenance that fail. **Failure Mechanism:** Physical, chemical, or other processes that may lead or have led to failure. **Failure Mode:** How the inability of an item to perform a required function occurs. **Hidden/Evident Failure:** Failure that is not detected during regular operation.

The explanation of each title in the Excel worksheet is gathered from the European Standard EN 13306 [44].

3.4 Comparison

Utilizing the comparative method, similarities, and differences between FPSOs and FOWTs are presented in Chapter 4, “Results and Discussion.” The method is used to view the similarities of failure modes between FPSOs and how the potential failure modes can be assumed for FOWTs. A detailed comparison between FPSOs and FOWTs is given in Chapter 2.3, “Comparison between FOWTs and FPSOs.”

4. Results and Discussion

This chapter comprehends the FMEA spreadsheet's results and key findings. It will also discuss the differences between an FPSO and an FOWT and how an FMEA of an FPSO can apply to an FOWT. The catenary mooring system analysed consist of the components shown in Figure 2-4.

4.1 FFA

The main function/function failure, identified by the number 1, and secondary function/function failure, identified by the number 2, are described based on the data from Appendix 1.

4.1.1 Mooring Line

The catenary system needs mooring lines to connect the floater and anchor at the seabed. A catenary mooring line consists of three parts: the first section is connected to the floater, which is often made of steel chain; a second section, which connects the first and third sections, which is often made of wire or synthetic rope; and the third section, which lays on the seabed and connects the anchor to the system.

Chain

The chain's main function is to connect the floating structure to the anchor. The chain is often on the top part of the mooring line connected to the floating structure and on the bottom part of the mooring line connected to the anchor. The main function failure is that the mooring line breaks. If the mooring line breaks, the FOWT will start drifting out of position, and potential hazards may occur. The chain's secondary function is to provide geometric stiffness to the mooring line, and its secondary function failure is poor load distribution on the mooring line. Main function/function failure and secondary function/function failure are described in Table 3.

Table 3 - Function/Function Failure for Chain

Function	**Function Failure**
1. Connect the floating structure to the anchor	1. Mooring line breaks
2. Geometric stiffness	2. Poorly load distribution

Wire Rope

The wire rope connects a part of the mooring line and is often a middle piece between the upper and lower chain. The main function of the wire rope, described in Table 4, is to connect the floating structure to the anchor, ensuring stability and position retention for the FOWT. If the main function fails and mooring line breakage happens, it poses a significant risk to the overall integrity of the mooring system; it could lead to detachment FOWT from the anchor, potentially causing drift, loss of position, or even complete system failure. The secondary function, described in Table 4, is to absorb tensions often generated by waves and currents. If the secondary function fails poorly, load distribution may occur, and the uneven load may lead to localized stress concentrations, leading to wear and, ultimately, structural failure of the wire rope.

Table 4 - Function/Function Failure for Wire Rope

Function	**Function Failure**
1. Connect the floating structure to the anchor	1. Mooring line breaks
2. Absorbing tension	2. Poorly load distribution

Synthetic Rope

The synthetic rope is like wire rope, with a mooring line between the upper and lower chain. Synthetic rope is favourable because of its lightweight compared to wire rope and chain. Synthetic rope's main function, described in Table 5, is to connect the floating structure to the anchor, ensuring stability and position retention for the FOWT. If the main function fails and mooring line breakage happens, it poses a significant risk to the overall integrity of the mooring system; it could lead to detachment FOWT from the anchor, potentially causing drift, loss of position, or even complete system failure. The secondary function, described in Table 5, is to reduce the mooring line's weight. If this fails poorly, load distribution may occur, and the uneven load may lead to localized stress concentrations, leading to wear and, ultimately, structural failure of the synthetic rope.

Table 5 - Function/Function Failure for Synthetic Rope

Function	**Function Failure**
1. Connect the floating structure to the anchor	1. Mooring line breaks
2. Weight reduction of mooring line	2. Poorly load distribution

4.1.2 Mooring Connectors

Connectors serve as vital links within the mooring line, facilitating the connection of components at crucial junctures like those between the floater and the anchor. In this thesis, the focus of the FMEA analysis will be on investigating selected connectors, namely Fairlead, H-Link, Tri-plate, In-line Tensioner and Shackle.

Fairlead

The fairlead's main function, described in Table 6, is to connect the floating structure to the mooring line. If this fails the floating structure can potentially drift from its initial position, posing a risk to the stability and integrity of the mooring system. The fairlead has no secondary function/function failure.

Table 6 - Function/Function Failure for Fairlead

Function	**Function Failure**
1. Connect the floating structure to the mooring line	1. Drifting floater

H-Link

The H-Link's main function, described in Table 7, is to connect mooring lines, often chained to polyester. If this fails, the mooring line disconnects and a drifting floater may occur, leading to risks of structural damage, loss of stability, operational disruption, or loss of assets.

Table 7 - Function/Function Failure for H-Link

Function	**Function Failure**
1. Connect two mooring lines	1. Mooring line disconnection

Tri-plate

The Tri-plate's main function, described in Table 8, is to connect mooring lines to buoy. If this fails, the subsurface buoy will disconnect, and the mooring line will sink or slam on the ground. This may lead to breakage of the rope, loss of stability in the mooring line, structural damage, etc.

Table 8 - Function/Function Failure for Triplate

Function	Function Failure
1. Connect the buoy to the mooring line	1. Subsurface buoy disconnection

In-Line Tensioner

The In-Line Tensioner's main function, described in Table 9, is to adjust the tension on the mooring line to the anchor. If this fails, an unbalanced tension may occur, which poses risks to the stability and security of the anchor. The secondary function, described in Table 9, is to hook up the mooring line to the AHV. If this fails, it might be the wrong layout in the mooring line, which can lead to wear on the chain, operational disruption, and safety hazards during anchor handling operations.

Table 9 - Function/Function Failure for In-Line Tensioner

Function	Function Failure
1. Adjusting tension	1. Unable to adjust tension
2. Hook-ups to AHV	2. Wrong layout in the mooring line

Shackle

The shackle’s primary function, described in Table 10, is to connect the chain to the pad eye of the anchor. If this fails, the anchor fails to connect to the mooring line, which may lead to the drifting of the floating structure, instability, safety hazards, potential damage to equipment, etc.

Table 10 - Function/Function Failure for Shackle

Function	**Function Failure**
1. Connect an anchor to the mooring line	1. Unable to connect anchor

4.1.3 Mooring Anchor

The anchor used in this report is a DEA. Its installation involves dragging it into the seabed using a mooring chain and an in-line tensioner designed to withstand horizontal forces. The DEA consists of a shank, fluke, and padeye. The shank efficiently transfers weight loads from the fluke to the mooring line while the fluke penetrates deep into the seabed.

Padeye

The pad eye's main function, described in Table 11, is to be used at a connection point between the shank and shackle, which is further connected to the chain. If this fails, the anchor will disconnect from the mooring line, making an unstable mooring system, which may lead to drifting of the floating structure, breakage of equipment, and potential hazardous events.

Table 11 - Function/Function Failure for Padeye

Function	**Function Failure**
1. Connection point between shank and mooring line	1. Disconnection to the mooring line

Shank

The shank's main function, described in Table 12, is to provide as the main body, holding capacity and connection between fluke and padeye. If this fails, the holding capacity of the anchor will fail, leading to potential unbalanced mooring system, which may lead to drifting of floating structure, breakage on equipment and potential hazardous events. The secondary function, described in Table 12, is to penetrate the seabed to get stability. If this fails, the anchor fails to install and instability will occur on the mooring system, which can lead to drifting floating structure, breakage on equipment, unadjusted tension, etc.

Table 12 - Function/Function Failure for Shank

Function	**Function Failure**
1. Connection between Fluke and Padeye	1. Holding capacity failure
2. Penetrate seabed	2. Anchor installation failure

Fluke

The fluke's main function, described in Table 13, is to provide the anchor with holding capacity. If this fail, the anchor will have no holding capacity and the function of the anchor will fail, which may lead to loosen mooring line, unstable system, unstable tension, etc.

Table 13 - Function/Function Failure for Fluke

Function	**Function Failure**
1. Provide anchor holding capacity	1. Holding capacity failure

4.1.4 Subsurface Buoy

Buoys are vital for protecting wire ropes in mooring system. Buoys elevate sections of the mooring line from seabed, reducing failure risks.

Buoy

The buoys main function, described in Table 14, is to elevate mooring line sections from the seabed. If this fails, the mooring line will not be elevated from the seabed and will slam into the seabed, causing the mooring line to weakening and potentially breakage of the mooring line. The secondary function, described in Table 14, is to provide stability to the system. If this fails unbalanced tension and forced may occur in the system, resulting in risks of wear and tear, breakage of equipment and other hazardous events.

Table 14 - Function/Function Failure for Buoy

Function	Function Failure
1. Elevate the mooring line section from the seabed	1. Elevation failure of mooring line
2. Stability of system	2. Failure to provide balance

4.1.5 Clump Weight

Clump weights are weights designed to distribute weight to lower chain part of the mooring line. It is typically three or more weights encircling the chain to establish connection.

Weights

The clump weight's main function, described in Table 15, is to make improved load performance. If this fails, failure of provide balance may occur, which can lead to wear and breakage of equipment because of wrong tensioning and unexpected force. The secondary function, described in Table 15, is to help provide desired geometric stiffness. If this fail, there will be uneven load distribution on the mooring line and unbalanced tension will occur, this may lead to breakage of equipment.

Table 15 - Function/Function Failure for Weights

Function	**Function Failure**
1. Load performance enhancing	1. Failure to provide balance
2. Desired geometric stiffness	2. Uneven load distribution

4.2 FMEA

This chapter presents the findings of a comprehensive Failure mode Effects and Analysis of the catenary mooring system for an FPSO. The analysis was conducted using information and data from FPSOs. The findings will be discussed to integrate the experience from the O&G industry into the FOWT industry.

4.2.1 Mooring Line

Chain

Chain is widely used in the offshore industry. New test pilot turbines, as of 2024, primarily utilize chains in their mooring systems. Chain is a familiar component and field proven in the O&G industry. The chain has some disadvantages, however. Chain links are weighty and prone to several failure mechanisms explained in Chapter 2.5. Chain links are a component the operators want to reduce in the future and replace them with synthetic fibre ropes [14]. A typical mooring system for a FOWT has mooring lines of approximately 2500 meters. This implies many chain links, which takes time and is expensive. On the other hand, the chain is reliable and well-known for its failure mechanism and profiles. Since both FOWTs and FPSOs utilize the same type of R4-R5 chain links, it is safe to assume that failure will eventually occur for chain links used in FOWT installations. The same type of mooring chains used in the O&G industry are used in the FOWT industry [14]. Therefore, is Table 16 highly relevant for a case study of a FOWT.

Table 16 - Failure Profile for Chain

Failure profile					
Hazard (5)	**Hazardous Event (4)**	**Failure Cause (1)**	**Failure Mechanism (2)**	**Failure Mode (3)**	**Hidden/Evident Failure**
Mooring line failure	*Breakage	Friction induced bending	Wear	*Out of plane bending	Hidden
Mooring line failure	*Breakage	Flawed flash welding	Manufacturing Defect	*Mechanical Damage	Hidden
Mooring line failure	*Breakage	Operational exposure	Installation issue	*Crack growth	Hidden
Mooring line failure	*Breakage	Hydrogen assisted cracking	Fatigue	*Crack growth	Hidden
Mooring line failure	*Breakage	Desing Flaw	Manufacturing Defect	*Mechanical Damage	Hidden
Mooring line failure	*Breakage	Load cycles	Fatigue	*Crack growth	Hidden
Mooring line failure	*Breakage	Microbially induced corrosion	Corrosion Fatigue	*Pitting corrosion	Hidden
Mooring line failure	*Breakage	Extreme conditions	Overload	*Crack growth	Hidden
Mooring line failure	*Breakage	Sulphur reducing bacteria	Corrosion Fatigue	*Pitting corrosion	Hidden
Mooring line failure	*Breakage	Marine growth	Wear	*Degradation	Hidden

Wire Rope

Operators apply wire ropes parallel to synthetic ropes. The operators can use both, and the failure profiles are similar. On the contrary, synthetic rope has a reputation for being more reliable. Wire ropes are stiffer and can hold high loads, and as of 2024, they were widely used by FPSOs. Typical failures related to Wire ropes usually arise from mechanical failure, installation, or external damage to the rope. See Table 17 for failure profiles for wire rope.

Table 17 - Failure Profile for Wire Ropes

Failure profile					
Hazard (5)	**Hazardous Event (4)**	**Failure Cause (1)**	**Failure Mechanism (2)**	**Failure Mode (3)**	**Hidden/Evident Failure**
Mooring line failure	*Disconnection	Malfunctioning retaining pin	Mechanical Failure	*Connector failure	Evident
Mooring line failure	*Breakage	Rubbing	External damage	*Rupture	Hidden
Mooring line failure	*Breakage	Extreme conditions	Overload	*Rupture	Hidden
Mooring line failure	*Breakage	Operational exposure	Installation Issue	*Rupture	Hidden

Synthetic Rope

Synthetic ropes are a component the industry wants to adapt to new concepts. Compared to the chain and wire rope, it has few failure modes. Synthetic ropes have lower stiffness, weight, and cost. There are several reasons why synthetic ropes are not a more significant part of the mooring system. First, the synthetic rope is not certified for seabed contact, so it needs a subsurface buoy. Secondly, according to specialists, it is challenging to do dynamic calculations on synthetic ropes [14]. Lastly, the test pilot FOWTs' operators apply technology they are familiar with, a catenary system that needs chains to maintain geometric stiffness. See Table 18 for failure profiles for synthetic ropes.

Table 18 - Failure Profile for Synthetic Ropes

Failure profile					
Hazard (5)	**Hazardous Event (4)**	**Failure Cause (1)**	**Failure Mechanism (2)**	**Failure Mode (3)**	**Hidden/Evident Failure**
Mooring line failure	*Breakage	Rubbing	External damage	*Rupture	Hidden
Mooring line failure	*Breakage	Operational exposure	Installation Issue	*Rupture	Hidden

4.2.2 Mooring Connectors

Fairlead

Fairleads are a component that secures the mooring line to the floater and allows possible tensioning with an AHV. Various types of fairleads are used in the O&G industry, but the thesis only includes the common denominator for all fairleads. Fairleads are mounted either in the splash zone or the splash zone is exposed to primarily environmental forces such as waves leading to abrasions. The fairleads are additionally exposed to weather forces and corrosion from the sea, potentially risking rusting, and degradation, leading to mechanical damage of the fairlead. The fairleads used by O&G may differ from those used by FOWTs, but the failure mechanism is the same with some variations. See Table 19 for failure profile for fairlead.

Table 19 - Failure Profile for Fairlead

Failure profile					
Hazard (5)	**Hazardous Event (4)**	**Failure Cause (1)**	**Failure Mechanism (2)**	**Failure Mode (3)**	**Hidden/Evident Failure**
Mooring line failure	*Breakage	Environmental conditions	Corrosion	*Degradation	Hidden
Mooring line failure	*Breakage	Abrasion	Wear	*Mechanical Damage	Hidden
Mooring line failure	*Breakage	Extreme conditions	Overload	*Mechanical Damage	Evident
Mooring line failure	*Breakage	Design flaw	Manufacturing Defect	*Mechanical Damage	Hidden

H-Link

H-links are a standard connector utilized by many operators and are familiar in the O&G industry. The failure mechanism for an H-Link is well known. However, there are some difficulties regarding H-links in different configurations. There has been a reported issue with environmental forces and movement in the floater knocking out pins and bolts from the H-link. This is a factor that a FOWT operator needs to be aware of. The pins can also be twisted if the line twists and turns. They are additionally referring to the Touch Down Point (TDP). If an H-link is placed near the TDP zone, it is exposed to slamming and abrasions, which can eventually lead to breakage. Connectors in a mooring line are typically considered "*weak spots*" [14]. See Table 20 for failure profile for H-link.

Table 20 - Failure Profile for H-Link

Failure profile					
Hazard (5)	**Hazardous Event (4)**	**Failure Cause (1)**	**Failure Mechanism (2)**	**Failure Mode (3)**	**Hidden/Evident Failure**
Mooring line disconnection	*Breakage	Microbially induced corrosion	Corrosion	*Degradation	Hidden
Mooring line disconnection	*Breakage	Extreme weather conditions	Overload	*Mechanical Damage	Evident
Mooring line disconnection	*Breakage	Environmental forces	Wear	*Degradation	Evident
Mooring line disconnection	*Breakage	Load cycles	Fatigue	*Crack growth	Evident
Mooring line disconnection	*Breakage	Design flaw	Manufacturing Defect	*Mechanical damage	Hidden

Tri-plate

Tri-plates are triangular-shaped connectors that connect typically subsurface buoys to the mooring line. Their failure profile is similar to that of the H-link. Due to its connecting point to buoyancy elements, the tri-plate may also be exposed to snap-loads. See Table 21 for failure profiles for tri-plate.

Table 21 - Failure Profile for Tri-plate

Failure profile					
Hazard (5)	**Hazardous Event (4)**	**Failure Cause (1)**	**Failure Mechanism (2)**	**Failure Mode (3)**	**Hidden/Evident Failure**
Buoy Disconnection	*Breakage	Microbially induced corrosion	Corrosion	*Degradation	Hidden
Buoy Disconnection	*Breakage	Extreme weather conditions	Overload	*Mechanical Damage	Evident
Buoy Disconnection	*Breakage	Environmental forces	Wear	*Degradation	Evident
Buoy Disconnection	*Breakage	Load cycles	Fatigue	*Crack growth	Evident
Buoy Disconnection	*Breakage	Design flaw	Manufacturing Defect	*Mechanical damage	Hidden

In-Line Tensioner

The in-line tensioner is a mechanical device that allows tensioning during installation and operation. The potential failure mechanisms are described in Table 22. A problematic issue with the in-line tensioner is the excess chain from the anchor. The excess chain is connected to a subsurface buoy for hookups with AHV. This chain and buoy are exposed to movement and potential additional failure.

Table 22 - Failure Profile for In-Line Tensioner

Failure profile					
Hazard (5)	**Hazardous Event (4)**	**Failure Cause (1)**	**Failure Mechanism (2)**	**Failure Mode (3)**	**Hidden/Evident Failure**
ILT failure	*Breakage	Microbially induced corrosion	Corrosion	*Degradation	Hidden
ILT failure	*Unable to interlock chain	Design flaw	Manufacturing Defect	*Mechanical Damage	Hidden
ILT failure	*Unable to interlock chain	Marine growth	Wear	*Mechanical Damage	Hidden
ILT failure	*Unable to interlock chain	Soil deposition	Mechanical Failure	*Mechanical Damage	Hidden
Mooring line failure	*Uneven load distribution	Unbalanced tension	Installation Issue	*Hackled lines	Hidden

Shackle

Shackles share many failure mechanisms with chain links. The thesis considers additional failure associated with the pin. A shackle is field-proven and familiar to many operators, but because it is a critical point, it might need strengthening. See Table 23 for failure profile for shackle.

Table 23 - Failure Profile for Shackle

Failure profile					
Hazard (5)	**Hazardous Event (4)**	**Failure Cause (1)**	**Failure Mechanism (2)**	**Failure Mode (3)**	**Hidden/Evident Failure**
Mooring line disconnection	*Breakage	Microbially induced corrosion	Corrosion	*Degradation	Hidden
Mooring line failure	*Loss of holding capacity	Extreme weather conditions	Overload	*Loss of anchor	Evident
Mooring line failure	*Loss of holding capacity	Environmental forces	External damage	*Loss of anchor	Evident
Mooring line failure	*Loss of holding capacity	Load cycles	Fatigue	*Loss of anchor	Evident
Mooring line failure	*Breakage	Design flaw	Manufacturing Defect	*Mechanical damage	Hidden

4.2.3 Mooring Anchor

Padeye

The padeye is where the Anchor is connected to the chain and is part of the shank. For that reason, the failure mechanism in the shank is the same as in the padeye. The padeye is exposed to heavy loads and needs to be designed accordingly. See Table 24 for failure profile for padeye.

Table 24 - Failure Profile for Padeye

Failure profile					
Hazard (5)	**Hazardous Event (4)**	**Failure Cause (1)**	**Failure Mechanism (2)**	**Failure Mode (3)**	**Hidden/Evident Failure**
Mooring line disconnection	*Breakage	Microbially induced corrosion	Corrosion	*Degradation	Hidden
Mooring line failure	*Loss of holding capacity	Extreme weather conditions	Overload	*Loss of anchor	Evident
Mooring line failure	*Loss of holding capacity	Environmental forces	External damage	*Loss of anchor	Evident
Mooring line failure	*Loss of holding capacity	Load cycles	Fatigue	*Loss of anchor	Evident
Mooring line failure	*Breakage	Design flaw	Manufacturing Defect	*Mechanical damage	Hidden

Shank

The shank is the middle section of the anchor, transferring the loads from the floater to the fluke. It is a simple section exposed to various failure mechanisms, as shown in Table 25.

Table 25 - Failure Profile for Shank

Failure profile					
Hazard (5)	**Hazardous Event (4)**	**Failure Cause (1)**	**Failure Mechanism (2)**	**Failure Mode (3)**	**Hidden/Evident Failure**
Mooring line failure	*Breakage	Microbially induced corrosion	Corrosion	*Degradation	Hidden
Mooring line failure	*Loss of holding capacity	Extreme weather conditions	Overload	*Loss of gravitational pull	Evident
Mooring line failure	*Loss of holding capacity	Environmental forces	External damage	*Loss of gravitational pull	Evident
Mooring line failure	*Loss of holding capacity	Embedded depth reduction	Wear	*Loss of gravitational pull	Evident
Mooring line failure	*Loss of holding capacity	Tilting	External damage	*Loss of gravitational pull	Evident
Mooring line failure	*Breakage	Load cycles	Fatigue	*Crack growth	Hidden

Fluke

The fluke is responsible for the anchor's holding capacity and shares the failure mechanism with the shank and padeye. If one section fails, the whole integrity of the anchor is compromised. See Table 26 for failure profile for fluke.

Table 26 - Failure Profile for Fluke

Failure profile					
Hazard (5)	**Hazardous Event (4)**	**Failure Cause (1)**	**Failure Mechanism (2)**	**Failure Mode (3)**	**Hidden/Evident Failure**
Mooring line failure	*Breakage	Microbially induced corrosion	Corrosion	*Degradation	Hidden
Mooring line failure	*Loss of holding capacity	Extreme weather conditions	Overload	*Loss of gravitational pull	Evident
Mooring line failure	*Loss of holding capacity	Environmental forces	External damage	*Loss of gravitational pull	Evident
Mooring line failure	*Loss of holding capacity	Embedded depth reduction	Wear	*Loss of gravitational pull	Evident
Mooring line failure	*Loss of holding capacity	Tilting	External damage	*Loss of gravitational pull	Evident
Mooring line failure	*Breakage	Load cycles	Fatigue	*Crack growth	Hidden

4.2.4 Subsurface Buoy

Buoy

The industry widely uses subsurface buoys, but for future reference, the subsurface buoys should not be included in an optimal mooring system for FOWTs. Subsurface buoys are prone to wear with much movement at points in the mooring system. In the O&G industry, there has been a reported issue of buoys wearing and tearing themselves from the mooring line, either from regular floating movement or under extreme weather conditions [14]. Subsurface buoys are, in addition, very difficult to inspect and install. Repairs and maintenance of subsurface buoys may result in unwanted costs. In a potential wind park, the failures associated with subsurface buoys will be high and a factor to be aware of, see Table 27 for failure profile for buoy.

Table 27 - Failure Profile for Buoy

Failure profile					
Hazard (5)	**Hazardous Event (4)**	**Failure Cause (1)**	**Failure Mechanism (2)**	**Failure Mode (3)**	**Hidden/Evident Failure**
Subsurface buoy disconnection	*Breakage	Extreme weather conditions	Overload	*Degradation	Evident
Subsurface buoy disconnection	*Breakage	Load cycles	Fatigue	*Degradation	Hidden
Subsurface buoy disconnection	*Breakage	Design flaw	Manufacturing Defect	*Mechanical damage	Hidden
Subsurface buoy disconnection	*Breakage	Operational exposure	Installation issue	*Crack growth	Hidden

4.2.5 Clump Weight

Weights

Clump weights are an unwanted component, often called "mooring accessories." Clump weights come with more issues than improvements. Their main objective is to increase mooring performance, but clump weights are difficult to install. Clump weights must be installed onboard an AHV and are therefore exposed to installation issues. There have also been incidents of losing clump weights [14]. The clump weights make it very difficult to inspect the chain below, therefore, the whole chain must be pulled up for inspection and maintenance, which is not very effective. Clump weights calculate the dynamics more complex and are a component that can be excluded from new concepts. The industry wants fewer components, and clump weights are not essential for a fully optimal mooring system. See Table 28 for failure profile for weights.

Table 28 - Failure Profile for Weights

Failure profile					
Hazard (5)	**Hazardous Event (4)**	**Failure Cause (1)**	**Failure Mechanism (2)**	**Failure Mode (3)**	**Hidden/Evident Failure**
Unbalanced Mooring System	*Breakage	Microbially induced corrosion	Corrosion	*Degradation	Hidden
Unbalanced Mooring System	*Uneven load distribution	Design flaw	Mechanical Failure	*Mechanical Damage	Hidden
Unbalanced Mooring System	*Breakage	Load cycles	Fatigue	*Degradation	Hidden
Unbalanced Mooring System	*Uneven load distribution	Operational exposure	Installation Issue	*Mechanical Damage	Evident

5. Future Directions and Recommendations

5.1 Integration of FMEA in Catenary Mooring Systems for FOWTs.

The FFA and FMEA carried out form a good basis for planning O&M of FOWTs. As the industry gains more experience from FOWT operations, the FMEA can be repeated and thereby continuously improve the basis for O&M. The authors of the thesis find the techniques applied in the O&G industry, applicable also for the wind industry conditional that key differences in concepts are understood. The thesis highlights similarities, differences, and potential areas for improvement. The thesis has investigated the possibilities for integrating a framework for FOWT based on FPSO experience. The thesis forms a solid groundwork for the development of FMEA into the lifecycle of FOWTs, including design optimization, risk assessment, operational monitoring, and maintenance planning to enhance reliability, safety, and performance.

5.2 Enhancing Reliability and Safety through Cross-Industry Knowledge Transfer.

This study is limited to available public papers and reports. It suggests a review of case studies, incident reports, and industry standards from the O&G sector to extract valuable insights into the management of mooring system risks and failures. It identifies possible transferrable knowledge, techniques, and methods that can be applied to deploy and maintain the catenary mooring system for a FOWT. Environmental conditions, operational requirements, and regulatory frameworks should be investigated in depth for future work. The offshore wind industry should seek knowledge and experiences from O&G installations to avoid making mistakes as was done in the early days for O&G projects and thereby ensure a high production efficiency from the very first start of the renewable era.

5.3 Recommendations for Improved Risk Management.

The authors of the thesis recommend guidelines and protocols for conducting comprehensive risk assessments and FMEA studies specific to catenary mooring systems for FOWTs, considering factors such as design complexity, material properties, and environmental loading conditions. And based on the lessons learned from the O&G industry, reviewing the historical failure incidents in the industry to conduct a comprehensive RCM report for a FOWT. Operators of FOWTs are strongly recommended to make experiences and monitoring data available in the public domain. This will allow the industry to learn and improve quicker than if operators keep such information internally. To reach corporate, national, and international goals for reduced CO_2 emissions a rapid and safe development of a floating offshore wind energy industry is most likely required.

6. Conclusion

FMEA is an efficient and frequently used tool for understanding how systems and components can fail and thereby a good support for designers or planners of O&M activities. There are many similarities and some differences in the behaviour of FPSOs and FOWTs. By cautiously considering the differences, established practice for FPSOs mooring systems can be applied also for FOWTs. The main differences relate to FOWTs being considered for relatively shallow and moderate water depths and thereby in need of components such as subsurface floaters and clump weights. For wind farms consisting of many FOWTs, such components are of concern both with respect to installability, replacement or repair. There is very limited information available in the public domain related to current practice for design, operation, and maintenance of mooring systems for FOWTs. By using knowledge from FPSOs in FMEA, it has been shown that it is possible to transfer the FPSO experiences to FOWTs in a structured and efficient way.

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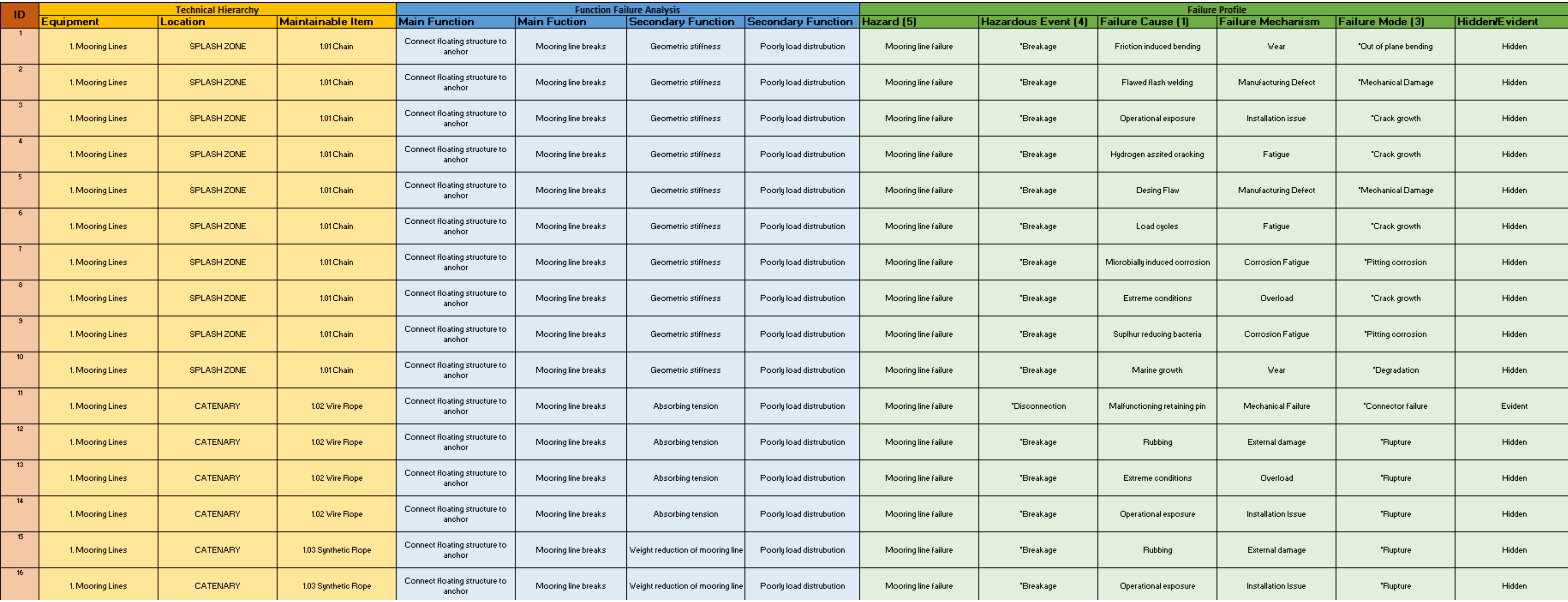
List of Figures

List of Tables

Appendix

Appendix 1 - Excel file: FMEA of Catenary Mooring System

Appendix 1



ID	Technical Hierarchy			Function Failure Analysis				Failure Profile					
	Equipment	Location	Maintainable Item	Main Function	Main Fuction	Secondary Function	Secondary Function	Hazard (5)	Hazardous Event (4)	Failure Cause (1)	Failure Mechanism	Failure Mode (3)	Hidden/Evident
1	1. Mooring Lines	SPLASH ZONE	1.01 Chain	Connect floating structure to anchor	Mooring line breaks	Geometric stiffness	Poorly load distrubution	Mooring line failure	'Breakage	Friction induced bending	Wear	'Out of plane bending	Hidden
2	1. Mooring Lines	SPLASH ZONE	1.01 Chain	Connect floating structure to anchor	Mooring line breaks	Geometric stiffness	Poorly load distrubution	Mooring line failure	'Breakage	Flawed flash welding	Manufacturing Defect	'Mechanical Damage	Hidden
3	1. Mooring Lines	SPLASH ZONE	1.01 Chain	Connect floating structure to anchor	Mooring line breaks	Geometric stiffness	Poorly load distrubution	Mooring line failure	'Breakage	Operational exposure	Installation issue	'Crack growth	Hidden
4	1. Mooring Lines	SPLASH ZONE	1.01 Chain	Connect floating structure to anchor	Mooring line breaks	Geometric stiffness	Poorly load distrubution	Mooring line failure	'Breakage	Hydrogen assited cracking	Fatigue	'Crack growth	Hidden
5	1. Mooring Lines	SPLASH ZONE	1.01 Chain	Connect floating structure to anchor	Mooring line breaks	Geometric stiffness	Poorly load distrubution	Mooring line failure	'Breakage	Desing Flaw	Manufacturing Defect	'Mechanical Damage	Hidden
6	1. Mooring Lines	SPLASH ZONE	1.01 Chain	Connect floating structure to anchor	Mooring line breaks	Geometric stiffness	Poorly load distrubution	Mooring line failure	'Breakage	Load cycles	Fatigue	'Crack growth	Hidden
7	1. Mooring Lines	SPLASH ZONE	1.01 Chain	Connect floating structure to anchor	Mooring line breaks	Geometric stiffness	Poorly load distrubution	Mooring line failure	'Breakage	Microbially induced corrosion	Corrosion Fatigue	'Pitting corrosion	Hidden
8	1. Mooring Lines	SPLASH ZONE	1.01 Chain	Connect floating structure to anchor	Mooring line breaks	Geometric stiffness	Poorly load distrubution	Mooring line failure	'Breakage	Extreme conditions	Overload	'Crack growth	Hidden
9	1. Mooring Lines	SPLASH ZONE	1.01 Chain	Connect floating structure to anchor	Mooring line breaks	Geometric stiffness	Poorly load distrubution	Mooring line failure	'Breakage	Suplhur reducing bacteria	Corrosion Fatigue	'Pitting corrosion	Hidden
10	1. Mooring Lines	SPLASH ZONE	1.01 Chain	Connect floating structure to anchor	Mooring line breaks	Geometric stiffness	Poorly load distrubution	Mooring line failure	'Breakage	Marine growth	Wear	'Degradation	Hidden
11	1. Mooring Lines	CATENARY	1.02 Wire Rope	Connect floating structure to anchor	Mooring line breaks	Absorbing tension	Poorly load distrubution	Mooring line failure	'Disconnection	Malfunctioning retaining pin	Mechanical Failure	'Connector failure	Evident
12	1. Mooring Lines	CATENARY	1.02 Wire Rope	Connect floating structure to anchor	Mooring line breaks	Absorbing tension	Poorly load distrubution	Mooring line failure	'Breakage	Rubbing	External damage	'Rupture	Hidden
13	1. Mooring Lines	CATENARY	1.02 Wire Rope	Connect floating structure to anchor	Mooring line breaks	Absorbing tension	Poorly load distrubution	Mooring line failure	'Breakage	Extreme conditions	Overload	'Rupture	Hidden
14	1. Mooring Lines	CATENARY	1.02 Wire Rope	Connect floating structure to anchor	Mooring line breaks	Absorbing tension	Poorly load distrubution	Mooring line failure	'Breakage	Operational exposure	Installation Issue	'Rupture	Hidden
15	1. Mooring Lines	CATENARY	1.03 Synthetic Rope	Connect floating structure to anchor	Mooring line breaks	Weight reduction of mooring line	Poorly load distrubution	Mooring line failure	'Breakage	Rubbing	External damage	'Rupture	Hidden
16	1. Mooring Lines	CATENARY	1.03 Synthetic Rope	Connect floating structure to anchor	Mooring line breaks	Weight reduction of mooring line	Poorly load distrubution	Mooring line failure	'Breakage	Operational exposure	Installation Issue	'Rupture	Hidden

17	1. Mooring Lines	BOTTOM	1.04 Chain	Connect floating structure to anchor	Mooring line breaks	Geometric stiffness	Poorly load distrubution	Mooring line failure	"Breakage	Flawed flash welding	Manufacturing Defect	"Mechanical Damage	Hidden
18	1. Mooring Lines	BOTTOM	1.04 Chain	Connect floating structure to anchor	Mooring line breaks	Geometric stiffness	Poorly load distrubution	Mooring line failure	"Breakage	Friction induced bending	Wear	"Out of plane bending	Hidden
19	1. Mooring Lines	BOTTOM	1.04 Chain	Connect floating structure to anchor	Mooring line breaks	Geometric stiffness	Poorly load distrubution	Mooring line failure	"Breakage	Flawed flash welding	Manufacturing Defect	"Mechanical Damage	Hidden
20	1. Mooring Lines	BOTTOM	1.04 Chain	Connect floating structure to anchor	Mooring line breaks	Geometric stiffness	Poorly load distrubution	Mooring line failure	"Breakage	Operational exposure	Installation issue	"Crack growth	Hidden
21	1. Mooring Lines	BOTTOM	1.04 Chain	Connect floating structure to anchor	Mooring line breaks	Geometric stiffness	Poorly load distrubution	Mooring line failure	"Breakage	Hydrogen assited cracking	Fatigue	"Crack growth	Hidden
22	1. Mooring Lines	BOTTOM	1.04 Chain	Connect floating structure to anchor	Mooring line breaks	Geometric stiffness	Poorly load distrubution	Mooring line failure	"Breakage	Desing Flaw	Manufacturing Defect	"Mechanical Damage	Hidden
23	1. Mooring Lines	BOTTOM	1.04 Chain	Connect floating structure to anchor	Mooring line breaks	Geometric stiffness	Poorly load distrubution	Mooring line failure	"Breakage	Load cycles	Fatigue	"Crack growth	Hidden
24	1. Mooring Lines	BOTTOM	1.04 Chain	Connect floating structure to anchor	Mooring line breaks	Geometric stiffness	Poorly load distrubution	Mooring line failure	"Breakage	Microbially induced corrosion	Corrosion Fatigue	"Pitting corrosion	Hidden
25	1. Mooring Lines	BOTTOM	1.04 Chain	Connect floating structure to anchor	Mooring line breaks	Geometric stiffness	Poorly load distrubution	Mooring line failure	"Breakage	Extreme conditions	Overload	"Crack growth	Hidden
26	1. Mooring Lines	BOTTOM	1.04 Chain	Connect floating structure to anchor	Mooring line breaks	Geometric stiffness	Poorly load distrubution	Mooring line failure	"Breakage	Suplhur reducing bacteria	Corrosion Fatigue	"Pitting corrosion	Hidden
27	1. Mooring Lines	BOTTOM	1.04 Chain	Connect floating structure to anchor	Mooring line breaks	Geometric stiffness	Poorly load distrubution	Mooring line failure	"Breakage	Marine growth	Wear	"Degradation	Hidden
28	2. Mooring Connectors	SPLASH ZONE	2.01 Fairlead	Connect floating structure to mooring line	Drifting floater			Mooring line failure	"Breakage	Enviromental conditions	Corrosion	"Degradation	Hidden
29	2. Mooring Connectors	SPLASH ZONE	2.01 Fairlead	Connect floating structure to mooring line	Drifting floater			Mooring line failure	"Breakage	Abrasion	Wear	"Mechanical Damage	Hidden
30	2. Mooring Connectors	SPLASH ZONE	2.01 Fairlead	Connect floating structure to mooring line	Drifting floater			Mooring line failure	"Breakage	Extreme conditions	Overload	"Mechanical Damage	Evident
31	2. Mooring Connectors	SPLASH ZONE	2.01 Fairlead	Connect floating structure to mooring line	Drifting floater			Mooring line failure	"Breakage	Design flaw	Manufacturing Defect	"Mechanical Damage	Hidden
32	2. Mooring Connectors	SPLASH ZONE	2.02 H-Link	Connect two mooring lines	Mooring line disconnect			Mooring line disconnection	"Breakage	Microbially induced corrosion	Corrosion	"Degradation	Hidden
33	2. Mooring Connectors	SPLASH ZONE	2.02 H-Link	Connect two mooring lines	Mooring line disconnect			Mooring line disconnection	"Breakage	Extreme weather conditions	Overload	"Mechanical Damage	Evident
34	2. Mooring Connectors	SPLASH ZONE	2.02 H-Link	Connect two mooring lines	Mooring line disconnect			Mooring line disconnection	"Breakage	Enviromental forces	Wear	"Degradation	Evident

35	2. Mooring Connectors	SPLASH ZONE	2.02 H-Link	Connect two mooring lines	Mooring line disconnect			Mooring line disconnection	'Breakage	Load cycles	Fatigue	'Crack growth	Evident
36	2. Mooring Connectors	SPLASH ZONE	2.02 H-Link	Connect two mooring lines	Mooring line disconnect			Mooring line disconnection	'Breakage	Design flaw	Manufacturing Defect	'Mechanical damage	Hidden
37	2. Mooring Connectors	CATENARY	2.03 Triplate	Connect buoy to mooring line	Subsurface buoy disconnection			Buoy Disconnection	'Breakage	Microbially induced corrosion	Corrosion	'Degradation	Hidden
38	2. Mooring Connectors	CATENARY	2.03 Triplate	Connect buoy to mooring line	Subsurface buoy disconnection			Buoy Disconnection	'Breakage	Extreme weather conditions	Overload	'Mechanical Damage	Evident
39	2. Mooring Connectors	CATENARY	2.03 Triplate	Connect buoy to mooring line	Subsurface buoy disconnection			Buoy Disconnection	'Breakage	Enviromental forces	Wear	'Degradation	Evident
40	2. Mooring Connectors	CATENARY	2.03 Triplate	Connect buoy to mooring line	Subsurface buoy disconnection			Buoy Disconnection	'Breakage	Load cycles	Fatigue	'Crack growth	Evident
41	2. Mooring Connectors	CATENARY	2.03 Triplate	Connect buoy to mooring line	Subsurface buoy disconnection			Buoy Disconnection	'Breakage	Design flaw	Manufacturing Defect	'Mechanical damage	Hidden
42	2. Mooring Connectors	BOTTOM	2.04 In-Line Tensioner	Adjusting tension	Unable to adjust tension	Hook ups to AHV	Wrong layout in mooring line	ILT failure	'Breakage	Microbially induced corrosion	Corrosion	'Degradation	Hidden
43	2. Mooring Connectors	BOTTOM	2.04 In-Line Tensioner	Adjusting tension	Unable to adjust tension	Hook ups to AHV	Wrong layout in mooring line	ILT failure	'Unable to inter lock chain	Design flaw	Manufacturing Defect	'Mechanical Damage	Hidden
44	2. Mooring Connectors	BOTTOM	2.04 In-Line Tensioner	Adjusting tension	Unable to adjust tension	Hook ups to AHV	Wrong layout in mooring line	ILT failure	'Unable to inter lock chain	Marine growth	Wear	'Mechanical Damage	Hidden
45	2. Mooring Connectors	BOTTOM	2.04 In-Line Tensioner	Adjusting tension	Unable to adjust tension	Hook ups to AHV	Wrong layout in mooring line	ILT failure	'Unable to inter lock chain	Soil depostions	Mechanical Failure	'Mechanical Damage	Hidden
46	2. Mooring Connectors	BOTTOM	2.04 In-Line Tensioner	Adjusting tension	Unable to adjust tension	Hook ups to AHV	Wrong layout in mooring line	Mooring line failure	'Uneven load distrubution	Unbalanced tension	Installation Issue	'Hackled lines	Hidden
47	2. Mooring Connectors	BOTTOM	2.05 Shackle	Connect anchor to mooring line	Unable to connect anchor			Mooring line disconnection	'Breakage	Microbially induced corrosion	Corrosion	'Degradation	Hidden
48	2. Mooring Connectors	BOTTOM	2.05 Shackle	Connect anchor to mooring line	Unable to connect anchor			Mooring line failure	'Loss of holding cpacity	Extreme weather conditions	Overload	'Loss of anchor	Evident
49	2. Mooring Connectors	BOTTOM	2.05 Shackle	Connect anchor to mooring line	Unable to connect anchor			Mooring line failure	'Loss of holding cpacity	Enviromental forces	External damage	'Loss of anchor	Evident
50	2. Mooring Connectors	BOTTOM	2.05 Shackle	Connect anchor to mooring line	Unable to connect anchor			Mooring line failure	'Loss of holding capacity	Load cycles	Fatigue	'Loss of anchor	Evident
51	2. Mooring Connectors	BOTTOM	2.05 Shackle	Connect anchor to mooring line	Unable to connect anchor			Mooring line failure	'Breakage	Design flaw	Manufacturing Defect	'Mechanical damage	Hidden
52	3. Mooring Anchor	BOTTOM	3.01 Padeye	Connection point between Shank and Mooring Line	Disconection to mooring line			Mooring line disconnection	'Breakage	Microbially induced corrosion	Corrosion	'Degradation	Hidden

53	3. Mooring Anchor	BOTTOM	3.01 Padeye	Connection point between Shank and Mooring Line	Disconection to mooring line			Mooring line failure	'Loss of holding cpacity	Extreme weather conditions	Overload	'Loss of anchor	Evident
54	3. Mooring Anchor	BOTTOM	3.01 Padeye	Connection point between Shank and Mooring Line	Disconection to mooring line			Mooring line failure	'Loss of holding cpacity	Enviromental forces	External damage	'Loss of anchor	Evident
55	3. Mooring Anchor	BOTTOM	3.01 Padeye	Connection point between Shank and Mooring Line	Disconection to mooring line			Mooring line failure	'Loss of holding capacity	Load cycles	Fatigue	'Loss of anchor	Evident
56	3. Mooring Anchor	BOTTOM	3.01 Padeye	Connection point between Shank and Mooring Line	Disconection to mooring line			Mooring line failure	'Breakage	Design flaw	Manufacturing Defect	'Mechanical damage	Hidden
57	3. Mooring Anchor	BOTTOM	3.02 Shank	Connection between Fluke and Padeye	Holding capacity failure	Penetrate seabed	Acnhor installation failure	Mooring line failure	'Breakage	Microbially induced corrosion	Corrosion	'Degradation	Hidden
58	3. Mooring Anchor	BOTTOM	3.02 Shank	Connection between Fluke and Padeye	Holding capacity failure	Penetrate seabed	Acnhor installation failure	Mooring line failure	'Loss of holding capacity	Extreme weather conditions	Overload	'Loss of gravitational pull	Evident
59	3. Mooring Anchor	BOTTOM	3.02 Shank	Connection between Fluke and Padeye	Holding capacity failure	Penetrate seabed	Acnhor installation failure	Mooring line failure	'Loss of holding capacity	Enviromental forces	External damage	'Loss of gravitational pull	Evident
60	3. Mooring Anchor	BOTTOM	3.02 Shank	Connection between Fluke and Padeye	Holding capacity failure	Penetrate seabed	Acnhor installation failure	Mooring line failure	'Loss of holding cpacity	Embedded depth reduction	Wear	'Loss of gravitaitonal pull	Evident
61	3. Mooring Anchor	BOTTOM	3.02 Shank	Connection between Fluke and Padeye	Holding capacity failure	Penetrate seabed	Acnhor installation failure	Mooring line failure	'Loss of holding cpacity	Tilting	External damage	'Loss of gravitaitonal pull	Evident
62	3. Mooring Anchor	BOTTOM	3.02 Shank	Connection between Fluke and Padeye	Holding capacity failure	Penetrate seabed	Acnhor installation failure	Mooring line failure	'Breakage	Load cycles	Fatigue	'Crack growth	Hidden
63	3. Mooring Anchor	BOTTOM	3.03 Fluke	Provide anchor holding capacity	Holding capacity failure			Mooring line failure	'Breakage	Microbially induced corrosion	Corrosion	'Degradation	Hidden
64	3. Mooring Anchor	BOTTOM	3.03 Fluke	Provide anchor holding capacity	Holding capacity failure			Mooring line failure	'Loss of holding capacity	Extreme weather conditions	Overload	'Loss of gravitational pull	Evident
65	3. Mooring Anchor	BOTTOM	3.03 Fluke	Provide anchor holding capacity	Holding capacity failure			Mooring line failure	'Loss of holding capacity	Enviromental forces	External damage	'Loss of gravitational pull	Evident
66	3. Mooring Anchor	BOTTOM	3.03 Fluke	Provide anchor holding capacity	Holding capacity failure			Mooring line failure	'Loss of holding cpacity	Embedded depth reduction	Wear	'Loss of gravitaitonal pull	Evident
67	3. Mooring Anchor	BOTTOM	3.03 Fluke	Provide anchor holding capacity	Holding capacity failure			Mooring line failure	'Loss of holding cpacity	Tilting	External damage	'Loss of gravitaitonal pull	Evident
68	3. Mooring Anchor	BOTTOM	3.03 Fluke	Provide anchor holding capacity	Holding capacity failure			Mooring line failure	'Breakage	Load cycles	Fatigue	'Crack growth	Hidden
69	4. Subsurface Bouy	CATENARY	4.01 Buoy	Elevate mooring line sections from seabed	Elevation failure of mooring line	Stability to system	Failure to provide balance	Subsurface buoy disconncetion	'Breakage	Extreme weather conditions	Overload	'Degradation	Evident
70	4. Subsurface Bouy	CATENARY	4.01 Buoy	Elevate mooring line sections from seabed	Elevation failure of mooring line	Stability to system	Failure to provide balance	Subsurface buoy disconncetion	'Breakage	Load cycles	Fatigue	'Degradation	Hidden

71	4. Subsurface Bouy	CATENARY	4.01 Buoy	Elevate mooring line sections from seabed	Elevation failure of mooring line	Stability to system	Failure to provide balance	Subsurface buoy disconncetion	'Breakage	Design flaw	Manufacturing Defect	'Mechanical damage	Hidden
72	4. Subsurface Bouy	CATENARY	4.01 Buoy	Elevate mooring line sections from seabed	Elevation failure of mooring line	Stability to system	Failure to provide balance	Subsurface buoy disconncetion	'Breakage	Operational exposure	Installation issue	'Crack growth	Hidden
73	5. Clump Weights	CATENARY	5.01 Weights	Load performance enhancing	Failure to provide balance	Desired geometric stiffness	Uneven load distribution	Unbalanced Mooring System	'Breakage	Microbially induced corrosion	Corrosion	'Degradation	Hidden
74	5. Clump Weights	CATENARY	5.01 Weights	Load performance enhancing	Failure to provide balance	Desired geometric stiffness	Uneven load distribution	Unbalanced Mooring System	'Uneven load distrubution	Design flaw	Mechanical Failure	'Mechanical Damage	Hidden
75	5. Clump Weights	CATENARY	5.01 Weights	Load performance enhancing	Failure to provide balance	Desired geometric stiffness	Uneven load distribution	Unbalanced Mooring System	'Breakage	Load cycles	Fatigue	'Degradation	Hidden
76	5. Clump Weights	CATENARY	5.01 Weights	Load performance enhancing	Failure to provide balance	Desired geometric stiffness	Uneven load distribution	Unbalanced Mooring System	'Uneven load distrubution	Operational exposure	Installation Issue	'Mechanical Damage	Evident
77	5. Clump Weights	BOTTOM	5.02 Weights	Load performance enhancing	Failure to provide balance	Desired geometric stiffness	Uneven load distribution	Unbalanced Mooring System	'Breakage	Microbially induced corrosion	Corrosion	'Degradation	Hidden
78	5. Clump Weights	BOTTOM	5.02 Weights	Load performance enhancing	Failure to provide balance	Desired geometric stiffness	Uneven load distribution	Unbalanced Mooring System	'Uneven load distrubution	Design flaw	Mechanical Failure	'Mechanical Damage	Hidden
79	5. Clump Weights	BOTTOM	5.02 Weights	Load performance enhancing	Failure to provide balance	Desired geometric stiffness	Uneven load distribution	Unbalanced Mooring System	'Breakage	Load cycles	Fatigue	'Degradation	Hidden
80	5. Clump Weights	BOTTOM	5.02 Weights	Load performance enhancing	Failure to provide balance	Desired geometric stiffness	Uneven load distribution	Unbalanced Mooring System	'Uneven load distrubution	Operational exposure	Installation Issue	'Mechanical Damage	Evident