An RCM program for inspection & maintenance of the substructure of a semi-submersible floating offshore wind turbine

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Preface

This bachelor thesis has been written in cooperation with Oceaneering. The bachelor was written during the spring semester 2022 at Western Norway University of Applied Sciences, Department of Mechanical and Marine Engineering in Bergen. The thesis is written by Simen S. Måge, Sindre Steinsbø and Petter Nuven.

We would like to thank Kato Setiady Larsen, Carina Berstad and all the other employees at Oceaneering for this opportunity and support during the project. We would also like to thank our supervisor and professor, Maneesh Singh, for guidance and support throughout the bachelor thesis. We would also like to show our appreciation to Peter Baastad, Arve Iversen and Kenneth Solbjør for great guidance about Oceaneering's ROVs. Finally, we would like to thank Hans Bjørne Lie from Equinor for good, useful, and up-to-date information about mooring system that have been shared with us.

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Abstract

To reduce the CO2 emission and achieve FN's sustainability goals, it is a possibility to use offshore wind as an energy source. Floating offshore wind is an alternative that have become popular over the years. As the technology for offshore wind is evolving, many companies want to get into the market, including Oceaneering.

The floating offshore wind industry is a young industry that is under development and is expected to grow in the coming years. Therefore, it is necessary to build knowledge on the technology and subject. This thesis presents a literary study of a semi-submersible FOWT (Floating Offshore Wind Turbine). An RCM (Reliability Centred Maintenance) program is also developed which highlights the most critical parts and presents a plan for both inspection and maintenance. The thesis also includes discussion on which of Oceaneering's ROVs that is best suited for the different inspection tasks in the inspection plan.

Companies that operate within offshore wind, including Oceaneering has provided up-to-date information for the thesis. Valuable information on mooring system, dynamic cables and ROVs has also been provided by experts in their respective fields. The information has contributed to a more accurate study. The conclusion of this thesis is that a RCM program will never be perfect and needs to be updated regularly after inspections, as new things may come up. It is also concluded that first-inspection shall be within 1 year, and then be done every 5 years after that. The interval shall never exceed 5 years. Maintenance shall be done when required. For these operations it is also concluded that for only visual inspection, Oceaneering's "Freedom AUV" shall be the preferred one, but for more detailed inspections Liberty E-ROV is recommended. If under some circumstances it is extreme weather conditions, the use of "Isurus" shall be discussed.

This bachelor thesis will present which parts of the system that is the most critical, but also a plan for the inspection & maintenance on the system, including the use of Oceaneering's next generation subsea vehicles.

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1. Introduction

1.1 Background

Over many decades the world has been exposed to high use of fossil fuels, and the climate has never been more affected by the CO_2 emissions. To prevent the climate changes, FN has set a goal to get climate neutral by 2030. To achieve this goal, the world needs new sources of energy.

For the last decade, offshore wind has become a new sustainable energy source. To achieve FN's sustainability goals, offshore wind will play a big part to goal number 7 which is to *"Ensure access to reliable, sustainable and modern energy at an affordable price"*. As the technology for offshore wind have come a long way, it still needs to evolve. New and better ways to perform maintenance needs to be found and there Oceaneering comes into the picture with its expertise within operations & maintenance.

Oceaneering is a company that thrives by creating industry-changing creative solutions for the most complex operational challenges subsea, onshore and in space. As a subsea engineering company, they recognize the importance of developing renewable energy and to reduce CO_2 emissions. Oceaneering has a successful record of accomplishment in the renewable energy industry. The company has been working on various projects such as wind turbine development and decommissioning. They work on both offshore renewables and hydrogen & carbon capture. This thesis will therefore supply insight into the inspection & maintenance on substructure of a floating offshore wind turbine.

1.2 Motivation

Oceaneering desires to be a company that can offer their services to the offshore wind industry in the future. The offshore wind industry is new, and it is necessary to build knowledge on the technology and subject. The industry is also growing fast with innovative solutions and technology being introduced. Many companies want to participate and provide their services to the industry which leads to tough competition. This means that if it is possible to acquire good knowledge early, then Oceaneering will be well placed for the future of the industry. Therefore, the motivation for this project will be to gain knowledge about the offshore wind industry and get to know what Oceaneering can offer the industry.

This project will look at the semi-submersible floating offshore wind turbine. The motivation is to find good solutions for maintenance and inspection for the semi-submersible floating wind turbine. A workable solution will mean that efficiency is high, and cost is low. It is necessary to have a system that can detect errors, suggest how to fix it and when to fix it. To do this a quality plan needs to be developed with consideration to maintenance and quality inspections. Inspection methods will also be discussed. All this will contribute to increased knowledge and suggest what Oceaneering can offer the industry.

1.3 Aim of project

The aim of the thesis is, to develop an RCM program for the semi-submersible FOWT and look at maintenance & inspection planning with use of Oceaneering's next generation ROVs.

1.4 Scope of work

The thesis will cover the following

- Study of substructures of offshore floating wind turbines.
- Develop an RCM program for the semi-submersible floating offshore wind turbine.
- Study and discuss inspection methods, and use of Oceaneering's next generation ROV's

1.5 Limitations

This bachelor thesis is written based on existing theories, standards, and literature. Most aspects of the project have been considered, and some simplifications have been made due to the lack of information. The proposed plan should only be used as a general guidance, as more detailed assessments and conditions may influence the proposed plan.

To finish the thesis in time and with all the resources available, limitations had to be set, and these are the most important:

- Focus on a three-blade turbine
- The substructure to be analyzed is the semi-submersible.
- Inspections suggested are being performed at long term moored column-stabilized units with no thruster assistance.
- The substructure parts of the semi-submersible foundation that will be evaluated in this thesis are hull (the floating foundation), mooring system and dynamic power cable.

1.6 Structure of Thesis

Chapter 1: Contains the background, the aim of the project, the scope of work, limitations, the structure of the thesis and abbreviations.

Chapter 2: A literature survey which contains: structure of wind turbines, substructures of offshore wind turbines, semi-submersible foundation, failure profile and inspection methods.

Chapter 3: Contains methods used and approaches taken to complete the study.

Chapter 4: Contains results and discussion.

Chapter 5: Conclusion.

Chapter 6: Recommendations for further work.

1.7 Abbreviations

AUV = Autonomous Underwater Vehicle

CO_2 = Carbon Dioxide

CoF = Consequence of Failure

DNV = Det Norske Veritas

DVI = Detailed Visual Inspection

ERDC = Engineer Research and Development Center

FFA = Functional Failure Analysis

FMECA = Failure Mode, Effects, and Criticality Analysis

FOWT = Floating Offshore Wind Turbine

GVI = General Visual Inspection

HSE = Health, Safety and Environment

I & M = Inspection & Maintenance

IMR = Inspection, Maintenance and Repair

m = meters

mm = millimetre

NDT = Non-Destructive Testing

OREDA = Offshore and Onshore Reliability Data

OROC = Onshore Remote Operations Center

PoF = Probability of Failure

PM = Preventive Maintenance

RCM = Reliability Centred Maintenance

ROV = Remotely Operated Vehicle

rpm = Revolutions per minute

TLP = Tension Leg Platform

USD = United States Dollar

2. Literature survey

A good understanding about offshore wind turbines is important to make a maintenance plan. This chapter will therefore include a description of how the different floating wind turbines are structured and diverse types of inspection methods. The literature survey also contains a description of failure profiles because this is important to know in order to both counter and prevent the failures that will occur. It will also contain a chapter on ROVs and inspection methods.

2.1 Structure of wind turbines

A wind turbine is a structure that uses the kinetic energy of wind to generate electrical energy. The energy in the wind helps the two or three blades spin around causing the rotor to spin. The rotor is connected to the main shaft, which spins a generator to create electricity. Then there is a low-speed shaft is turned at about 30-60 rpm. The low-speed s shaft is connected to a high-speed shaft which are increasing the rotational speeds from 30-60 rpm to about 1000-18000 rpm. The speed at which a wind turbine generates electricity is known as the rotor speed. A rotational speed of 1000-18000rpm is what most generators need to produce electricity. It is also controlled by a pitch system that forces the blades to pitch out of the wind to avoid turning in unfavourable conditions. This is a critical aspect of the safety system of the wind turbine.

The nacelle is found at the top of the tower and holds the gear box, low and high-speed shafts, generator, controller, and brakes. There is installed a brake to stop the rotor electrically, mechanically, or hydraulically, in case of emergencies. The yaw drive is a vital component that is used to keep the wind turbines aligned with the wind's direction to maximize their output. Downwind turbines do not require a yaw drive because the wind manually turns the rotor the correct way.

An anemometer is placed on the outside of the nacelle. The anemometer measures speed and direction of the wind and feeds data to the controller. The controller starts up the machine at wind speeds of about 3.5 to 7 m/s and shuts off the machine at about 25 m/s. Turbines does not run at wind speeds above 25 m/s because they may be damaged by high wind speeds. Next to the anemometer there is a wind vane, which measures wind direction and communicates with the yaw drive to orient the wind turbine properly with respect to the wind. [19]

There are two types of wind turbines. There are offshore and onshore wind turbines. A key difference between these two are the consistency they can generate energy. The wind speed offshore is both higher and more consistent. Which makes the offshore wind farm capable of generating electricity at a steadier rate compared with their onshore counterparts. Offshore turbines may require more creativity when it comes to foundations, depending on the depths of the operating site.

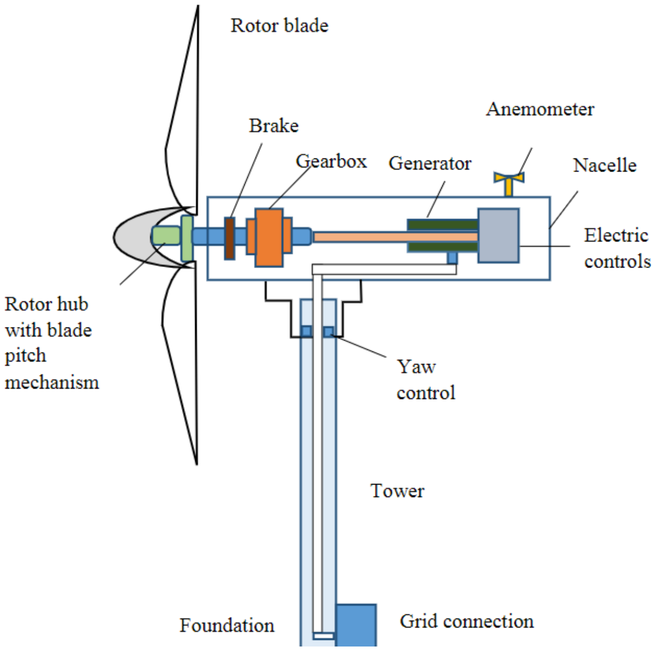

Figure 1 - Structure of windtubine

2.2 Substructures of offshore wind turbines

An offshore wind farm is a type of electricity generation system that uses the wind to generate electricity from floating or submerged bodies of water. These facilities are usually found in areas of water with high wind speeds. Most offshore wind farms are in shallow water. However, floating wind turbine installations are in the initial stages of development. The cost of onshore wind power has always been lower than offshore. However, it became more competitive with traditional power sources in 2017. As of 2020, less than 1 percent of the world's electricity is generated by offshore wind farms.

There are many diverse types of offshore wind turbine structures as shown in Figure 2. On the left there is three bottom fixed structures known as monopile, jacket and tripod. Three floating structures is shown at the right known as semi-submersible, Tension Leg Platform (TLP) and spar buoy. [33]

Figure 2 - Offshore wind substructures

2.3 Semi-submersible foundation

This thesis will only consider the semi-submersible Floating Offshore Wind Turbine (FOWT). The semi-submersibles are likely to be one of the most used designs for floating offshore wind turbines in the future, considering many companies base their designs on semi-submersibles.

The semi-submersible wind turbine foundation consists of the turbine, the tower, and the hull. The hull consists of three columns that provide stability. The columns are submerged with pontoons that provide buoyancy. The semi-submersibles have low vertical motion but in more extreme weather it is dependent on a flexible mooring system to maintain its position. It is most common to position the turbine tower on top of one of the columns, with additional ballast in the two other columns. For energy transportation, the turbines are equipped with dynamic power cables connected to a power network or an installation.

The semi-submersible foundations provide a lot of advantages for their use in the offshore wind industry. This type of foundation has been used in the oil and gas industry and is a proven and well-known structure for deep and harsh environments. The foundation can be installed at a wide range of depths normally from 40m to 300m depending on technology from the current company. This increases the reach of wind farms and the depths they can be installed. The foundation is using a well-known and simple mooring system that has been used for a long time for foundations in the oil and gas industry. The semi-submersible structure is very mobile and can easily be transported between onshore ports and offshore sites. This allows for a wider use on different sites and allows the turbine to be towed back to port for more complex maintenance operations. The foundation can also be fully assembled onshore before being towed to site. The hull and the tower get assembled in the port, which for other foundations is being done at sea, and reduces risks for the operation. Installations at least 10 km from shore will reduce the risk to migratory birds and minimize visual impact. [33]

Some of the challenges with the semi-submersible foundation is that it has a large and heavy structure which requires more material. This increases costs and ensures a more complex manufacturing of the foundation. Also, the foundation is more affected by motion from high waves than other types of foundation. The foundation also requires ongoing inspection and maintenance. Mooring systems and cables can disrupt sea life, and there are possibilities of carrying invasive species while towing to site. [3]

The substructure parts of the semi-submersible foundation that will be evaluated in this thesis are:

- Hull (the floating foundation)
- Mooring system
- Dynamic power cables

Figure 3 - Semi-submersible FOWT

2.3.1 Mooring System

The mooring system is an important part of the FOWT as it holds the foundation at its station. The mooring system consists of anchors, mooring lines, and fairleads. There are different mooring systems, with variety in number of lines, line length and configuration. Factors that decide what mooring system to use are water depth and type of FOWT structure.

The common mooring configuration for the semi-submersible is catenary. The catenary configuration consists of 6 lines that must be longer than the onsite sea depth. For the catenary mooring system, the motion of the floaters is limited by the weight of the lower part of the mooring line. Lateral forces are absorbed by the mooring line moving up and down in the water. The catenary mooring system has a horizontal connection to the seabed, and the degree of free movement for the FOWT is horizontal. The horizontal chain that rests on the seabed results in large seabed disruption. [18]

2.3.1.1 Mooring lines

The mooring lines can consist of a combination of steel chain, steel wire rope and synthetic fiber ropes. [19]

The most common mooring line type is steel chain. The chain is available in varied sizes and grades. The diameters are available normally between 25mm to 180mm. The grades are decided in consideration of quality of the steel and the provided strength.

Wire ropes are made of steel like chains. The advantages with a wire rope are that it is lighter and more elastic but can still handle the same loads as the chains. The disadvantages are that the wire rope is more likely to corrode and receive damage. To avoid corrosion polyethylene jacketing can be provided.

Synthetic fiber ropes are a qualified technology for mooring and that has been proved in several projects. The most suitable for FOWT is the polyester rope and it is now widely used. The polyester rope is a parallel laid construction of several smaller sub ropes. The advantages with the fiber rope are the reduction in weight and cost, and the fiber rope does not corrode. [7]

The best mooring system for the semi-submersible floating wind turbine is the catenary mooring system. A floating wind turbine typically has 3 or 6 mooring lines. These are connected to the substructure with a bridle. A combination of steel chain and steel wire is used due to the deep waters the semi-submersible FOWT is sited at. The chain is necessary in the seabed section of the catenary mooring system because the weight of the chain avoids vertical loads, and the chain can handle abrasion. It is also used in the upper part due to simplification of adjusting the line length and the tension, and to connect the line to the FOWT. The wire rope is beneficial in the water column due to weight and cost when the FOWT is in deep waters. Figure 4 shows an example of composition for a mooring line. [18]

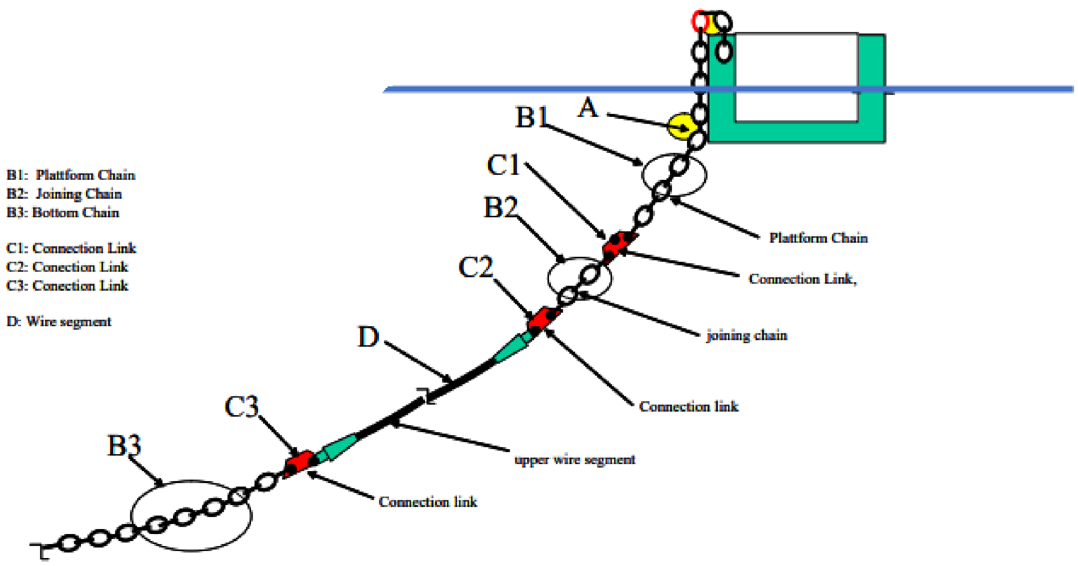

Figure 4 - Example of composition for a mooring line [18]

2.3.1.2 Anchors

There are several types of anchors, some based on suction or gravity, and some are drag embedded. The choice of anchor depends on soil condition, water depth and the load on the anchor. Common anchors used on FOWT are suction anchors and drag embedded anchors. The drag embedded anchor is dragged across the seabed to penetrate it. The anchor uses the resistance of the soil to withstand forces. The anchor is best suited to resist horizontal forces, although modern anchors also manage well against vertical forces. The suction anchor is a steel pipe with a closed top. The anchor is forced into the seabed using a pump located on the top of the pipe. When forcing the anchor into the seabed, the pump removes water inside the pipe, creating a pressure difference between the outside and the inside. The anchor uses friction from the soil and the lateral soil resistance to withstand forces and is therefore suited to resist vertical and horizontal forces. [7]

2.3.1.3 Fairleads

The fair leads shown in figure 5) are used as a mooring line guide. The fair leads are important for the mooring line to lead it in the desired direction and to keep the demanded angle between the lines. The line will be prevented for lateral movement but be able to move freely in the desired direction. The fair lead also prevents the line from rubbing to undesired surfaces.

Figure 5 - Example of fairlead [18]

2.3.2 Hull

The semi-submersible hull was designed back in the 1960s and has later been used in the oil and gas industry. In modern days, many companies are basing their structures on semi-submersible design.

The hull consists of columns, pontoons and diagonal braces between the columns and pontoons. The columns provide stability, the pontoons provide buoyancy, and the braces ensure structural integrity between the columns and pontoons. The number of columns varies from three to four depending on where the turbine tower is located. The pontoons are submerged into the columns. [3]

The movement the hull experiences creates a lot of forces and stresses for the structure and the mooring lines. Semi-submersible structures have six degrees of freedom: heave, sway and surge in the translational degree, and roll, yaw, and pitch in the rotational degree. Movement to these degrees creates stress and fatigue in the various parts of the FOWT substructure. [21]

2.3.3 Dynamic power cable

With the floating wind industry growing the demand of dynamic power cables will also increase. With floating windfarms far from shore and deep water the technicality on the cables needs to improve and change also. The power cables are used for power transmission between the FOWT power generation installation and to the shore or an installation. For transmission to the shore there are likely to be fixed cables to the seabed. The cable between the seabed and the FOWT will be the dynamic power cable which is a part of the substructure of the semi-submersible FOWT. [13]

The FOWT requires a dynamic, high-capacity submarine cable system to collect and export the generated power. The cable is dependent on floating elements that enable the cable to move in team with the FOWT. The cable is continuously affected by movement from the ocean in relation to the floating turbine and is also affected by its own weight that creates bending and twisting forces on the cable. [30]

2.4 Failure profile of semi-submersible FOWT

Knowing hazards that causes failure of the semi-submersible structure of an FOWT, and how those failures create risks and need for maintenance of the wind turbine is important to both counter and monitor the failures that will occur. This subchapter will therefore include causes of failure/ failure profile and what type of failures that may occur. Many of the failure causes will apply for more than one of the components on the semi-submersible FOWT.

2.4.1 Corrosion

Corrosion is a process that occurs when a metal gets exposed to a chemical reaction that causes deterioration. For a corrosion to occur, the following conditions must be fulfilled. (1) Metal surface exposed to the environment, (2) Water containing ions, the electrolyte must be able to conduct current or (3) An oxidant (e.g., oxygen, carbon dioxide).

If one of these conditions is not present, there will be no corrosion. The types of corrosion that is most common are: External corrosion, hydrogen induced stress cracking, internal corrosion, microbiologically induced corrosion and galvanic corrosion. Chain is not typically coated or protected, so the lack of protection is accounted for in design by imposing a wear and corrosion allowance. The requirements for wear and corrosion vary between industry guidelines and design codes. The allowance can range from 0.2 mm/year to 0.8 mm/year depending on a set of factors. An example can be weather the chain is an almost static position on the seabed or in the active splash zone area. Table 1 shows corrosion allowance on a DNV-GL-OS-E301 standard. In general, corrosion is a visual degradation mechanism which can be monitored by scheduled inspection. [21]

Part of mooring line	*Corrosion allowance to be added to chain diameter (mm/year)*		
	Regular inspection 1)	*Requirements for the Norwegian continental shelf*	*Requirements for tropical waters*
Splash zone	0.4	0.8 2)	1.0
Catenary 3)	0.3	0.2	0.3
Bottom 4)	0.4	0.2	0.4

1) The regular inspection is carried out by ROV in accordance with DNVGL-RU-OU-0102 or in accordance with operator's own inspection program, approved by national authorities if necessary.
2) The increased corrosion allowance in the splash zone is required by NORSOK M-001.
3) Suspended length of mooring line below the splash zone and always above the touchdown point.
4) The corrosion allowance specified in the table is provided as guidance. Significantly larger corrosion allowance than the minimum values recommended in the table should be considered if microbiologically induced corrosion (MIC) can be expected.

Table 1 - Corrosion allowance for chain (DNV-GL-OS-E301)

Figure 6 - Corrosion on chain

2.4.2 Fatigue failure

Fatigue failures shown in figure 7 occur in parts which are exposed to alternating, or fluctuating stresses. Fatigue cracking is a type of stress fracture that usually occurs at stress raisers. It starts at a localized spot and gradually starts spreading over a cross section until the component or member completely collapses. The primary cause of fatigue failure is a critical localized tensile stress. This type of stress is difficult to evaluate and design for. From the appearance of the fractured surface, it is possible to recognize a fatigue failure. There are three factors necessary to cause fatigue failure; (1) maximum tensile stress of sufficiently high value. (2) a large enough variation or fluctuation in the applied stress and (3) a sufficiently substantial number of cycles of the applied stress. Other factors such as corrosion, geometric transitions, and thermal expansion are also known to contribute to the formation of localized stress. These conditions can also affect the structure and properties of the component.[34]

Figure 7 - Chain link fatigue failure

2.4.3 Erosion

The term erosion refers to "*the process of removing surface material because of several factors such as gas bobbles (cavitation), solid particles, and liquid droplets*". [28] This type of degradation is time dependent but can sometimes cause rapid failure. The mildest type of erosive wear appears as a light polishing of surfaces, but in its worst form can cause considerable material loss. [28]

2.4.4 Wear and tear

Wear and tear of the chain is a challenge due to the enormous forces at the substructure. The wear of the link is accelerated as the floating structure moves continuously due to the forces of wind, wave, and current. Even with small movements, the contact stress in these areas can still cause unacceptable chain wear rates. The cyclic hinging action of the links can also cause significant wear on the shoulders and links immediately following the fairlead rock onto the chain wheel. This type of damage is triggered by the rotation of the links following changes in catenary angle. An example of adhesive wear in the interlink zone is showed at figure 8. [4,6]

Figure 8 - Adhesive wear in the interlink zone

2.4.5 Marine growth

Marine growth in figure 9 is a simple factor that can cause many problems. Speaking in a general sense, "marine growth" would refer to all life in the ocean, including aquatic plants, shellfish, and fish. In this report marine growth will be used as a term to specifically refer to problematic species that attach or grow on the subsea structures of a FOWT. The marine growth can both add weight and drag to a structure, this will also make inspections more difficult due to difficulties getting a clear view of the structure. This must be accounted for in the design phases. Marine growth can come in many different forms but are divided into hard, which is animals such as muscles and barnacles and soft, which is seaweeds and kelp. [26]

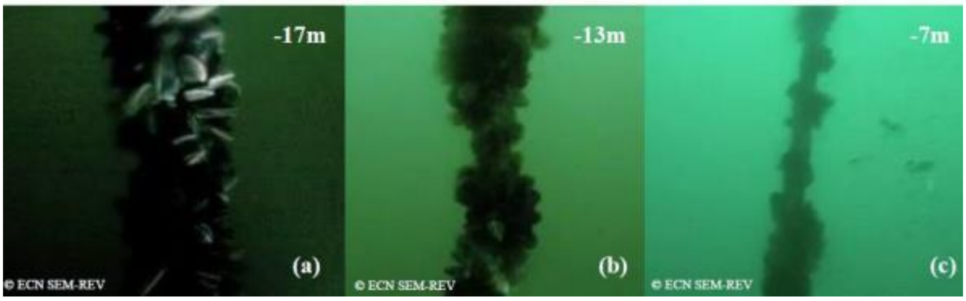

Figure 9 - Marine growth on chains

The different failure profiles and what causes these failures have, has been described. The most important failure profiles are corrosion, fatigue failure, erosion, wear and tear and marine growth. The next step is to look at what inspection methods that can be used to discover these failures before they get critical.

2.5 Inspection methods

Inspection of floating wind turbines are important to prevent unexpected failures. Throughout an inspection plan, intervals for when inspections need to be performed is set and what types of inspections that need to be done. Through inspection, the manufacturer and customer get reassured that the product lives up to the quality that is needed.

There are many ways to perform inspection, but for subsea operations ROV-technology (Remotely Operated Vehicle) is the most preferred. A ROV is an underwater vehicle mostly used for industrial, scientific, and military operations. The ROVs are used from water's surface, but in the last few years, Oceaneering as a leading ROV-technology company has developed OROC (Onshore Remote Operations Center). By remotely controlling the ROVs from an onshore centre, the efficiency will be increased while reducing costs, HSE risk, and carbon footprint.

A ROV has a quite uncomplicated design, it has a main body, with thrusters, lights, video and stills cameras. They can also carry extra equipment, for example grabbers and suction samplers. The ROVs get electrical power from umbilical connected to the surface, but also command and control signals to the vehicle is being sent through the umbilical.

2.5.1 Next generation ROVs

Oceaneering is a leading company within ROV-technology and has developed three of the next generation subsea vehicles. Whether it is a need for a resident to stay underwater for a long time or a need to take advantage of the short weather windows during an operation, Oceaneering has the right vehicle for the job. [31]

Isurus ROV

The Isurus in figure 10 is built on the success of the "Magnum Plus ROV" and combines full work class capabilities with best-in-class performance in high-current environments, which is making it ideal for renewables and high-speed ROV surveys. In comparison to the Magnum Plus, Isurus has a more hydrodynamic design with incredibly powerful thrusters. Traditional ROVs are usually limited to speeds of 1.5 to 2 knots, this is where the Isurus stands out with its speed up to 5 knots. This will make the Isurus able to complete work more efficiently, on-time and cost-effectively. [24]

Figure 10 - Oceaneering's Isurus ROV

Liberty E-ROV

Oceaneering's Liberty E-ROV in Figure 11 is a battery-powered, work-class vehicle that can perform easy routine tasks with few deployments. It is also used for carrying out inspection, maintenance, and repair (IMR), commissioning, and underwater intervention activities.

A big advantage by using the Liberty E-ROV, is reducing the carbon footprint by up to 90%. Compared to a vessel based ROV operation, an estimate shows that the emissions go down from 51000 lbs a year to 5000 lbs when Liberty is used.

With the OROC it is backed by 24/7 onshore support, and it can be operated from locations located all over the world. The onshore centre can connect and communicate with the Liberty ROV via 4G LTE and satellite communication, which makes it a very cost-effective subsea tool.

Equipment highlights:

- Revolutionary ROV concept with high end technology.
- 500kWh Li-Ion battery power bank.
- Surface communications buoy equipped with 4G LTE and satellite communication.
- All-in-one deployed and recovered ROV, garage, winch, and buoy system.
- OROC support with remote piloting.
- Cost effective subsea tool.

Through testing of the Liberty E-ROV it is estimated that it can save up to seven days of IMR vessel time, which can save the client up to 1 million USD (United States Dollar). [25]

Figure 11 - Oceaneering's Liberty E-ROV

Freedom Autonomous Vehicle

The Freedom Autonomous Vehicle (Figure 12) is a combination of a ROV and an AUV (Autonomous Underwater Vehicle) into one system, which makes it very flexible and efficient. The "Freedom" usually performs tasks like, pipeline survey, seabed survey, close visual inspection, and light intervention activities. This vehicle is also supported by a docking station that is located at the seabed, this gives it a hybrid functionality because it can be remotely piloted, via tether or through-water communications, or autonomous mode. [17]

Features:

- Low altitude pipeline inspection
- Pipeline detection
- Pipeline Acquisition
- Pipeline following
- Pipeline crossing detection
- Freespan detection
- Object detection
- Know Object avoidance and DVI (Detailed Visual Inspection)
- Unknown object avoidance and GVI (General Visual Inspection)
- Pipeline crossing inspection
- Freespan inspection

Figure 12 - Oceaneering's Freedom AUV

2.5.2 Use of ROV compared to other Inspection methods

The report [15] which was conducted by the ERDC's Center for Remote R&D Engineering, explains how ROVs can help decrease the number of divers needed for hazardous inspections. Instead of having to rely on highly trained divers, ROVs can be used to thoroughly inspect underwater areas and keep the divers in a safer environment. Benefits of using ROV as an inspection method instead of divers:

- Compared to diving activities, operating an ROV is less hazardous.
- ROVs are installed with tools that can help improve the efficiency of various asset management activities. They can perform various tasks such as inspecting locations, tracking repairs, and reducing costly maintenance.
- Unlike divers, ROVs are not limited to the physical limitations of humans. They can also submerge to depths of up to 200-300 meters. This allows them to work in harsh environments and provide real-time data about the conditions of the water. Some types can also be deployed down to thousands of meters.
- According to an ERDC study, ROVs have a better cost-benefit ratio than divers when it comes to performing underwater inspections.
- For divers, the prolonged operation time of ROVs is due to the additional safety stops that they must make to avoid decompression sickness. For ROVs, the time spent underwater depends on the weather and the availability of a ROV pilot.

Other factors such as the weather conditions and the complexity of the tasks that ROVs can perform are also limiting their capabilities in offshore areas. These limitations include:

- Like divers, ROVs are prone to experiencing difficulties operating in harsh weather conditions. While working underwater, the crew members are also affected by the weather conditions.
- Due to the ROV's limited thrust, it is usually harder to work in areas with high current speeds. This impairs its ability to carry out large tasks.
- Since the ROV pilot operates using the lights and cameras on board, muddy areas and depths can also cause issues for the ROV.
- Although ROVs are commonly used for offshore projects, there are still some tasks that require the expertise of experienced divers:

- Assist vessel problems underwater
- Recovery of dropped objects
- Repair and cleaning tasks
- Installations underwater
- Other similar duties

2.6 Requirements for inspection of semi-submersible FOWT

The inspection is performed to obtain condition data for the semi-submersible FOWTs equipment on site. The condition data will be used to decide further actions for maintenance and inspection. The inspection should identify the different failure mechanisms discussed in chapter 2.4, and fulfil requirements discussed in this chapter.

2.6.1 Hull

The semi-submersible shall be examined in line with the requirements for column-stabilized units, or for some areas ship shaped units might be applicable. For the hull, the ROV shall inspect external surfaces of underwater areas forming part of the buoyant volume when the unit is afloat. The inspection is performed as visual inspection with measurement in addition, and with NDT (Non-Destructive Testing) if necessary. Results from the inspection shall be documented in a report that contains pictures, descriptions, and locations of findings. Inspections shall take place annually with first inspection within a year after installation, then inspections frequently without exceeding 5 years. Inspection scope increases for every inspection after the first annual inspection. This range is from spot checks (2-5%) to full inspection of hull (100%). For the range rated as 50% or 25%, inspection shall cover selected critical parts or a selected number of parts. [9]

Table 2, which is based on standard DNVGL-RU-OU-0300 [9], shows a suggested plan for inspections with consideration to annual inspections. The table shows a minimum of what to inspect and the scope of inspection for primary external parts of the hull with ROVs.

Visual inspection of external hull under water with use of ROV			
	First annual inspection (within 1 year)	Annual inspection (5years)	Annual inspection (10years +)
Horizontal bracings		A	A
Vertical/diagonal bracings		C	A
Column and pontoon shell		C	A
External hull	X	X	A
Column to pontoon		C	A
Pontoon to pontoon		C	A
Fairleads	X	C	A
	Inspection scope: A = 100%, B = 50%, C = 25%, X = spot check 2-5%		

Table 2 - Visual inspection of external hull under water with use of ROV [9]

2.6.2 Mooring lines

The mooring for semi-submersible FOWT will currently be long-term mooring. The applicable requirements will be based on new designs for mooring lines and for mooring without help from thrusters. Inspections for the mooring system can be performed with a system in use, so there should be no disruption to operation. Owner of the unit shall provide an inspection plan with criteria based on observations from past inspections. Several documentations shall also be available and include records for maintenance and repairs, records for mooring line, reports from earlier inspections, documents for tension of mooring line and certificates for all installed equipment.

The inspection needs good access and lighting. In addition to visual inspection, it might be necessary with opening up and NDT of selected parts. Critical parts shall be thoroughly inspected and subjected to NDT if necessary.

1st annual inspection should be performed after installation of the mooring system, within a year when the system has settled. These inspections should mostly be visual. The inspection that shall be performed by ROV should cover all components on the mooring line from anchor to connectors located at the hull. This inspection shall record conditions compared to recording from installation inspection of the mooring line and document it with pictures, descriptions, and locations. This shall all be submitted in a report for the inspection.

Further annual inspections shall be performed within every 5 years. The inspection scope will apply as additions to the 1st annual inspection. The inspection shall be visual, with measurements and with NDT if necessary. Detailed Visual Inspection (DVI) shall also be carried out for some critical parts. Background information must be provided from previous findings and information. Mooring lines shall be compared to previous inspections. An inspection report shall be recorded with pictures, descriptions and locations for findings and observations. All abnormalities shall be documented. At least 25% of the lines shall be inspected and not less than 2 lines shall be included. If the ROV inspection detects critical defects, a more detailed inspection shall be carried out involving DVI. [9]

2.6.3 Dynamic cable

For dynamic cable continuous monitoring and inspection is necessary to record status for the cable system. Inspection with ROV shall mostly be under the same circumstances as with the mooring system. External inspections shall be performed to ensure that design requirements remain at that no damage occurs. The intervals for inspection may vary and shall be decided with relation to several conditions but shall never exceed 5 years. These conditions include operator requirements, risk of failure, results from previous inspections, changes in operation, sea dynamics and requalification. Inspection results shall be documented with pictures, descriptions, and locations, and be available as information for future inspection. [8]

Section 4 results and discussion, in the report will further discuss how to inspect, what to inspect, where to inspect, and suggest suitable types of ROVs for the inspection operations of the semi-submersible FOWT.

3. Methods & Approach

3.1 Methods

Both quantitative and qualitative methods are used for gathering information. The former uses statistical techniques to gather data, but literature surveys can also be used. While the latter uses literature or surveys to investigate the observed. A combination of these methods will be used in this thesis. Literature covering the inspection and maintenance will have to be studied and accounted for.

3.2 Adopted Approach

Information on the structure of a floating wind turbine is especially important to understand its substructure. This thesis aims to gather the necessary details to properly implement an inspection and maintenance plan. Literature describing the substructure and inspection & maintenance planning will be researched.

3.3 RCM

The concept of reliability centred maintenance (RCM) is a technique utilized for developing a program that will ensure the reliability of an equipment. It assumes that the build quality and design of the system are the factors that determine its reliability. [27]

RCM is designed to provide the most cost-effective solution for the project. Its goal is to minimize the risk of system failure while still achieving the best possible performance. A successful PM (Preventive Maintenance) task involves identifying and addressing the root cause of a system failure. It must also minimize the expected loss due to several factors such as environmental damage and material damage. Although RCM can help identify the cause of a system failure, it should not be used as a replacement for poor design or inadequate maintenance.

An RCM analysis is carried out as a sequence of different steps:

1. Study Preparation
2. System selection & definition
3. Functional failure analysis (FFA)
4. Critical item selection
5. Data collection and analysis
6. FMECA (Failure Mode Effect Criticality Analysis)
7. Selection of maintenance actions
8. Determination of maintenance intervals
9. Preventive maintenance comparison analysis
10. Treatment if non-critical items
11. Implementation
12. In-service data collection and updating

3.3.1 Study Preparation

Before the project begins, the group must establish the objectives and the scope of the analysis. It should also make sure that the requirements and acceptance criteria are clearly defined. Other documents such as the process diagrams and piping and instrumentation diagrams should also be made available. Since the resources that are available for analysis are usually limited, the group should not focus on cost analysis alone.

3.3.2 System selection and definition

Before deciding to perform an RCM analysis, two things should be discussed.

1. To which systems are an RCM analysis beneficial compared with more traditional maintenance planning?
2. At what level of assembly (plant, system, subsystem) should the analysis be conducted?

Although all systems may benefit from an RCM analysis, we should first make sure that the systems that are most likely to benefit are identified and prioritized.

In most plants, an assembly hierarchy is a set of systems that work together to provide some sort of output. In the oil and gas industry, this assembly hierarchy is used as a tag number system. An offshore oil and gas platform is typically considered a plant. A system is a set of subsystems that perform a main function in a plant. An offshore gas production platform may have a gas compression system that is considered a system.

The assembly hierarchy can be broken down into subsystems. The lowest level of the hierarchy is typically the analysis items. An analysis item is a system component that can perform at least one significant function on its own. For example, a shutdown valve is typically an analysis item, while the actuator is typically a supporting equipment.

The importance of distinguishing the various analysis items from their supporting equipment is also highlighted in the FMECA. If an analysis item has no significant failure modes, then it should not be addressed. If the analysis item has only one major failure mode, then the supporting equipment should only be analysed to see if there are other potential causes of that failure.

Usually, the maintenance tasks and intervals for analysis items are decided by the RCM approach. When it comes to performing a maintenance task, the focus usually involves identifying and repairing or testing a component or part of the analysis item. The analyst should keep the analysis at the highest practical level. Doing so will help define the performance standards for the various analysis items. The selection and organization of the analysis items should be clear and unambiguous. If the OREDA database is used in later phases of the analysis, then the items should be defined in accordance with the equipment units in OREDA.

3.3.3 Functional failure analysis (FFA)

After selecting system in step 2, objectives in this step need to be performed.

1. Identify and describe the system's required functions and criteria of performance,
2. Describe input interfaces required for the system to operate, and
3. To identify the ways in which system might fail to function.

Step 3(1): Identification of system functions

The system of a plant will have a high number of functions. Having a checklist or a classification scheme will help the analyst identify the various system functions that are most critical to the operation. Items with hidden failures are considered protected ones. However, discussions about which functions should be classified as essential or auxiliary should be avoided.

Step 3(2): Identification of interfaces

The various system functions may be represented by functional block diagrams or flowcharts. In some cases, they may be separated into subfunctions on an increased level of detail.

Step 3(3): Functional failures

The next part of the process is a functional failure analysis (FFA), this is to identify the potential failure modes of the system. There are a variety of schemes and classifications for identifying the most critical failures. These failures need to be classified, as followed.

Sudden failures – Failures that could not be forecast by anyone.,

Gradual failures - The types of failures that could be expected to occur over time are referred to as gradual failures. They can be easily recognized if they are compared to the performance of the device.

Aging failures - The aging failure is a gradual failure that occurs when the performance of the analysed item gradually drops. This type of failure can happen even if the device is designed to resist. This is also an important type of failure.

Functional failure – The functional failure is recorded on a specific FFA worksheet (Table 3 & 4), which is like a standard FMECA worksheet. An example is shown below. The various operational modes of the system are presented in the first column of Fig. 2. The performance requirements for each function are listed in the third column. While all the relevant system functions are recorded in column 2. In the fourth column, all the system functions' relevant functional failures are listed. In column 5-8 a criticality ranking is provided. The reason this ranking is included is to limit the scope of the analysis by ignoring minor functional failures. The criticality must be judged on plant level, and is ranked in four consequence classes:

- S: Safety of personnel
- E: Environment impact
- A: Production availability
- C: Material loss (costs)

The criticality of a function may be ranked according to the following categories: high (H), medium (M), low (L), and negligible (N). If even one of the four entries is a medium or high criticality, the criticality of the functional failure shall be placed as significant.

The frequency of a functional failure can also be categorized in four categories. These classes can be used to prioritize the most critical issues. If the frequency and criticality of a functional failure are low or negligible, it should be ignored in the further analysis.

System	Subsystem	Maintainable Unit / Part	Functions	Failure Effect	Risk (Safety)	Risk (Environmental)	Risk (Economic)	Critical / Noncritical
			-	-				

Table 3 - Functional Failure Analysis

Probability of Failure	Consequence of Failure (Safety)	Consequence of Failure (Safety) - Notes	Consequence of Failure (Environmental)	Consequence of Failure (Environmental) - Notes	Consequence of Failure (Economic)	Consequence of Failure (Economic) - Notes

Table 4 - Functional Failure Analysis

Risk Matrix

A risk matrix (Table 5) is a tool to help identify the risks for a system or operation. The risk is the consequence of something happening in relation to the probability of something happening. The CoF ranking are categorised in Environmental, Economic and Safety. Then they each get a rank for the consequence and possibility of each category and the risks can be read out of the risk matrix. This matrix is used in this project to decide which rank the different failure modes has in the FFA.

	CoF Ranking				
- Environmental	A - Slight Pollution	B - Minor Pollution	C - Moderate Pollution	D - Major Pollution	E - Massive Pollution
- Economical	A - Slight Damage	B - Minor Damage	C - Moderate Damage	D - Major Damage	E - Massive Damage
- Economical	A - Slight Loss	B - Minor Loss	C - Moderate Loss	D - Major Loss	E - Massive Loss
- Safety	A - No Injury	B - Minor Injury	C - Major Injury	D - Single Fatality	E - Mulitple Fatality
5 - Expected	3 - Medium	4 - High	4 - High	5 - Very High	5 - Very High
4 - High	3 - Medium	3 - Medium	4 - High	4 - High	5 - Very High
3 - Medium	2 - Low	3 - Medium	3 - Medium	4 - High	4 - High
2 - Low	1 - Very Low	2 - Low	3 - Medium	3 - Medium	4 - High
1 - Negligible	1 - Very Low	1 - Very Low	2 - Low	3 - Medium	3 - Medium
- Safety	No Injury	Minor injuries, with short recovery time	Injuries, with some recovery time	Serious injury with longer recovery time	Irreversible or fatal injury.
- Safety	No Injury	Minor cuts, falling and getting a few scratches	Cuts that might need stitches, sprained ankles	Significant cuts, broken arms or legs	Serious head trauma, drowning
	Rarely	Unikely	Possibly	Likely	Almost Certainly

Table 5 - Risk Matrix

3.3. 4 Critical item selections.

This step aims to identify the items that are most critical to the performance of the system. These items are usually referred to as functional significant items.

For simple systems, the existence of the critical items can be identified. For complex systems, this step may require a formal approach. It can be performed using various techniques such as fault tree analysis, reliability block diagrams, and Monte Carlo simulation. Aside from the FSIs, we also need to consider the existence of other critical items such as low maintainability, high failure rate, and long lead time for spare parts.

A combination of MCSIs and FSIs are used and are denoted as MSI (Maintenance significant items). In the FMECA worksheet, all the MSIs (Maintenance Significant Items) is going to be analysed to identify potential failures and effects.

3.3.5 Data collection and analysis

The various phases of the analysis typically involve the use of various data sources. These include design data, operational data, and reliability data. Which will be discussed in this section. Reliability data is especially important to analyse a system's criticality. It can help determine the system's failure process and provide an optimized time between PM-tasks. It includes:

- MTTF (Mean time to failure)
- MTTR (Mean time to repair)
- Z(t) (failure rate function)

Sometimes, the increasing failure rate may be related to the condition of the critical items and that the item is deteriorating. If it is decreasing, it is a sign that the system is improving. It may happen that the item is both increasing and decreasing in different intervals.

The operational and reliability data are collected from various sources that have similarities with the operating conditions of the system. These include data banks, data handbooks, and manufacturers' recommendations. Before it is used, the external data collected from external sources should be thoroughly analysed and considered before it is used.

In some cases, the lack of reliable data can lead to the development of a maintenance program that is customized to the new system. This can be done by using the experience and knowledge gathered from other similar sources, such as manufacturers and data banks. Even in this situation, the RCM will provide useful information.

3.3.6 FMECA

The objective of doing the FMECA-step is to find the dominant failure modes of the MSIs which is identified in step 4. Several types of FMECA worksheets are used in the main RCM references. The FMECA worksheet (table 6) provides a more detailed view of the system. The different columns are:

Number			Failure Mode & Mechanism		Effect					Maintenance Planning		Inspection Planning		Reference
System	Subsystem	Maintainable Unit	Failure Mode	Failure Mechanism	Local Effect	Global Effect	Hidden / Evident	Dangerous Failure	Failure Development	Maintenance Task	Maintenance Interval	Inspection task	Inspection interval	

Table 6 - FMECA

MSI:

- The tag number of the analysis item

Operational mode:

- MSI can have different modes to operate in, like running and standby.

Function:

- For each mode the MSIs operate in, it has several functions.

Failure mode:

- A failure mode is a behaviour that occurs when a failure is not fulfilled.

Effect of failure:

- The effect of a failure is described in terms of the worst-case outcome for the various categories introduced in Step 3. The criticality may be specified by the same four classes or by some numerical severity measure.

Worst case probability:

- The worst-case scenario is a prediction of how an equipment failure will affect the system. A system model is required to obtain a numerical probability measure.

MTTF:

- The time it takes for an equipment failure to occur in different failure modes is recorded. It can be computed by taking a numerical measure or by adding likelihood classes to the list.

Criticality:

- The criticality field is used to identify the dominant failure modes. A criticality measure should consider the worst-case probability and MTTF.

Failure cause:

- Each failure mode has a different type of cause. For instance, an MSI failure may be caused by multiple components. In this context, a failure caused by a supporting equipment may be considered a failure mode.

Failure Mechanism:

- For each failure mode, there are multiple failure mechanisms that can be identified. Some of these include fatigue, corrosion, and wear.

Failure characteristic:

This is divided into three classes:

- The failure propagation can be measured using a variety of indicators, such as condition monitoring. Which is referred as “gradual failure.”
- The probability of failure is age dependent. It can be estimated that the wear-out limit of an asset is predictable. Which makes it a “aging failure.”

- The time to failure can only be described by an exponential distribution, and it is not possible to predict when a failure will occur. This is referred as an “sudden failure.”

Maintenance action:

- The decision logic can now find an appropriate maintenance action for each failure mechanism. However, this field can only be completed after Step 7.

Failure characteristic measure:

- The condition monitoring indicators for gradual failures are listed by name. The aging parameter is also recorded in the Weibull distribution.

Recommended maintenance interval:

- This column will present the interval between each of the maintenance tasks that is given.

3.3.7 Selection of Maintenance Actions

This step is the most novel approach in maintenance planning. It uses a decision logic to guide an analyst through a series of questions. The main idea of the decision is to determine if a PM task should be performed following a failure or if a corrective maintenance task should be performed after the asset has already failed.

The main reasons to perform a PM task:

- Prevent failures
- Detect the failure onset
- Discover hidden failures

The basic maintenance task to consider is:

- *On-condition task*
- *Overhaul*
- *Replacement*
- *Function test*
- *Run to failure*

For an *on-condition* task to be performed, the analyst must meet three requirements. These include identifying the condition of the asset, performing a follow-up analysis, and recommending a maintenance action. Following criteria need to be met for the task to be applicable:

- It must be possible to detect the reduced failure resistance of a specific failure mode.
- It must be possible to define a potential failure condition that can be detected by an explicit task.
- The age interval between potential failure and functional failure should be consistent.

Scheduled *overhauls* are usually performed on an item before its age limit. However, these tasks are only considered if the following requirements are met:

- The item must have an identifiable age at which its failure rate increases rapidly.
- A substantial portion of units must meet this age limit to be considered for maintenance actions.
- It must be possible to restore the item's original failure resistance by reworking its components.

Scheduled *replacement* is the replacement of an item that is at or before the age of its specified limit. This should be done if following circumstances is met:

- Close to critical failure.
- Test data shows that no failure is expected to occur below given life limit.
- Subject to a failure that has big economic consequences.
- An identifiable age of when the item shows an increased ratio in the FRF (failure rate function).
- Huge proportion of units need to survive to the given age.

The scheduled *function test* is a task that can be performed to identify hidden functions. It avoids surprises by probing the hidden function. The following conditions need to be met for a function test task to be applicable:

- The item must be subjected to a functional failure that is not apparent to the operating crew.
- If no other task is applicable or effective.

Run to failure is a deliberate decision to perform an unsuccessful task. It avoids performing other tasks that are not required to be done. The PM task cannot prevent all failures. However, it can help prevent some of them by identifying a potential failure mode and performing a proper follow-up task. If the failure has economic and operational consequences, then the redesign may be desirable. However, this should be done in a cost-benefit manner. The criteria for selecting an appropriate task should therefore only be considered as guidelines for the proper use of the various tasks.

3.3.8 Determination of maintenance intervals

The decision logic in the figure below applies to the various PM tasks. Usually, the tasks are performed at regular intervals. However, choosing an optimal interval can be challenging due to several factors such as the failure rate, the cost of the task, and the risk of the failure. The various tasks typically involved in maintaining a system are grouped into maintenance packages. Doing so prevents the maintenance intervals from being optimized for each specific task.

Most practitioners avoid using models to improve the maintenance intervals by relying on the manufacturers' recommendations. Doing so often leads to deficient performance and too frequent maintenance. This is because they tend to rely on the manufacturers' recommendations and experience. Procedure of determining maintenance intervals is described in Figure 13.

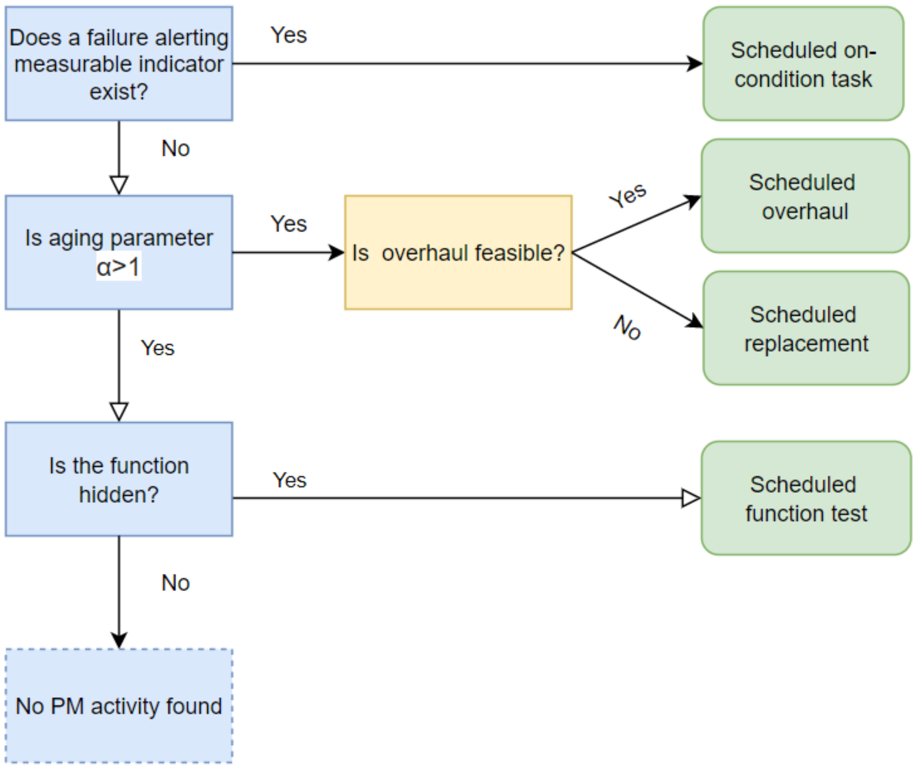

Figure 13 - Procedure of determining maintenance intervals, based on Marvin Rausand's theory. [27]

3.3.9 Preventive maintenance comparison analysis

For selecting maintenance tasks, two criteria are used. Both requirements must be met for each task selected:

- *Effective*
- *Applicable*

Applicability:

The applicability criteria consider the task's relevance to the knowledge and consequences of a failure. If a task can reduce a failure rate or reduce the impact of a failure, then it should be considered.

Cost-effectiveness:

The effectiveness of a maintenance task is a measure of how well it is performing its intended function. It also helps determine if performing the task is worth the effort. Costs of an PM task can include:

- Cost related to maintenance induced failures
- Risk the personnel is exposed to when performing the task.
- An increase in the likelihood of failure of another component can increase the risk of an issue with this system.
- Cost of equipment and physical resources.
- The unavailability of physical resources elsewhere is increased while carrying out this task.
- No production under maintenance task.

The cost of a failure may be:

- A failure can have various consequences. These include, but are not limited to, loss of production, safety violations, and accidents
- Even if it has already failed, failing to perform the PM task still has negative consequences (loss of warranty, etc.)
- Emergency repairs, which will make personnel work overtime, high replacement costs and expediting costs.

3.3.10 Treatment of non-MSIs

In Step 4, the critical items were identified for further analysis. However, what to do with the non-critical items that were not analysed? Before the project begins, it is important to carry out a cost evaluation for all existing maintenance programs. If the existing maintenance cost related to the non-MSI's is insignificant, it is reasonable to continue this program.

3.3.11 Implementation

The findings of the RCM analysis should be based on the availability of the various technical and organizational support functions. This is a requirement to minimize the risk of accidents. It is also important to consider the various risks associated with the various tasks involved in a maintenance program. An analysis of these risks can help identify possible human errors and minimize the risk of accidents.

3.3.12 In-service data collection and updating

One of the main advantages of analysing and documenting the basis for decisions is that it allows us to make better decisions based on the data we have available. The process of updating should be concentrated on three major time perspectives, including:

- Short term interval adjustments
- Medium term task evaluation
- Long term revision of the initial strategy

Each significant failure should be compared to the failure characteristics of the FMECA. If the data is not covered properly, the relevant parts of the analysis should be revised.

The short-term update may be used to review the previous analysis results. It can also be used to update the reliability estimates and failure information. Doing so should not require many resources as the framework is already established. Only Steps 5-8 in the RCM process will be affected by short term updates while the medium-term update will more carefully review the basis for the selection of maintenance actions in Step 7. The long-term revision will consider all steps in the analysis while also consider all the factors that affect the plant's operation. It should also consider the various contractual considerations and new laws governing the environment. This may also require an updated FMECA in Step 6 if new significant failure causes not considered in the initial analysis is discovered.

4. Results & discussion

In this section, the results will be presented and discussed. An RCM program has been developed to highlight which parts of the system that is critical, and a specific inspection & maintenance plan has been made. Throughout the RCM program there has also been performed an FMECA of the FOWT to identify, prioritize and eliminate potential failures from the system before they reach the costumer. This is to make sure that all failure modes and their effects on operational success of the system has been considered. This will also provide a basis for both inspection and maintenance planning. The results and discussion will also contain a comparison of Oceaneering's different ROV's to be used for inspection and maintenance of the FOWT.

4.1 Function Failure Analysis

The Function Failure Analysis describes each maintainable part, their function and what effect a failure of said part may cause. Through the FFA, the functions and failure effects of each maintainable part is described. Based on data from "*A developed failure mode and effect analysis for floating offshore wind turbine support structures*" [1], which presents reliability data for failure modes on FOWTs. PoF (Probability of Failure) and CoF (Consequence of Failure) has been decided on a rank from 1-5. The FFA (Table 7) also gives a highlight of the risk of safety, environment and economic of each maintainable part, and based on these three factors it is decided which part that is critical or noncritical for the system.

System	Subsystem	Maintainable Unit / Part	Functions	Failure Effect	Probability of Failure	Consequence of Failure (Safety)	Consequence of Failure (Safety) - Notes	Consequence of Failure (Environmental)	Consequence of Failure (Environmental) - Notes	Consequence of Failure (Economic)	Consequence of Failure (Economic) - Notes	Risk (Safety)	Risk (Environmental)	Risk (Economic)	Critical / Noncritical
Substructure of floating wind turbine	Mooring system	Mooring lines	Keep the structure in place, take loads from environment (currents, winds, and waves)	Malfunction of whole system, the FOWT cannot locate in water	2 - Low	C - Major Injury	Danger for vessels nearby, and possible inspection & maintenance personnell	B - Minor Pollution	Minor pollution, no danger of chemical leaks	E - Massive Loss	Big economic loss, due to damage and cost of operations to get the turbine up and running	3 - Medium	2 - Low	4 - High	Critical
Substructure of floating wind turbine	Mooring system	Anchors	Secure the wind turbine to seafloor	anchor failure, detaches from the seabed	2 - Low	C - Major Injury	Danger for vessels nearby, and possible inspection & maintenance personnell	C - Moderate Pollution	Moderate pollution, no danger of chemical leaks, material leaks can occur, muddy sea	E - Massive Loss	Big economic loss, due to damage and cost of operations to get the turbine up and running	3 - Medium	2 - Low	4 - High	Critical
Substructure of floating wind turbine	Mooring system	Fairlead	guide the mooring lines and anchor, drop and lift	Anchor and mooring lines cannot be dropped and lift	3 - Medium	B - Minor Injury	Minor damage will occurr, no danger for nearby vessels	C - Moderate Pollution	Moderate pollution, no danger of chemical leaks, material leaks can occur	C - Moderate Loss	Moderate economic loss, not a major part of the FOWTs function	3 - Medium	3 - Medium	3 - Medium	Critical
Substructure of floating wind turbine	Electrical	Dynamic cables	Deliver power/communication to the FOWT, and send power/communication onshore	No communication and power to the wind turbine	2 - Low	A - No Injury	No damage will occurr to nearby vessels or possible inspection & maintenance personnel	C - Moderate Pollution	Moderate pollution, no danger of chemical leaks, material leaks can occur	D - Major Loss	Major economic loss, due to damage on electrical and time to fix	1 - Very Low	3 - Medium	3 - Medium	Noncritical
Substructure of floating wind turbine	Floating Foundation	Pontoons and columns	Make the FOWT float and makes it very stable	Unstable structure, which can lead to capsizing	2 - Low	E - Multiple Fatality	Hazardous. If personnel on board, death may occur. Can damage nearby vessels with people onboard	D - Major Pollution	Major pollution if capsizing, chemical leaks and material leaks(plastic etc.)	E - Massive Loss	Big economic loss, due to damage and cost of operations to get the turbine up and running	4 - High	3 - Medium	4 - High	Critical
Substructure of floating wind turbine	Floating Foundation	Braces between pontoons and columns	keep the structure stable	can lead to more strain/stress on other components, which make it more unstable and lead to other failures	2 - Low	B - Minor Injury	Minor damage will occurr, no danger for nearby vessels	A - Slight Pollution	Slight pollution, no chemical leaks	D - Major Loss	Major economic loss, due to damage on braces and time to fix	2 - Low	1 - Very Low	3 - Medium	Noncritical

Table 7 - FFA of semi-submersible FOWT

As presented in the FFA (table 7), the most critical parts for the semisubmersible FOWT are mooring lines, anchors, fairlead, and pontoons & columns. Common for all these critical parts, is that the average risk between safety, environment and economic is medium or higher. An average risk below medium is considered noncritical which includes the dynamic cables and braces between pontoons & columns. When the FFA is complete, and it is decided with background in data's which part that is critical or noncritical, the next step was performing an FMECA.

4.2 Failure Mode, Effects and Criticality Analysis

The FMECA describes failure modes & mechanisms and effects of each maintainable unit of the system. Every maintainable unit has a failure mode and different failure mechanisms that causes the failure mode. Examples of this can be wear, fatigue, corrosion, marine growth etc. Each failure mode also has a local effect and a global effect. Local effect means the effect the failure has on the system, and global means the effect the failure has for the company that owns the FOWT, environment, economic loss etc. It also contains sections with maintenance & inspection planning, which includes maintenance task, maintenance interval, inspection task and inspection interval.

Number			Failure Mode & Mechanism		Effect					Maintenance Planning		Inspection Planning		Reference
System	Subsystem	Maintainable Unit	Failure Mode	Failure Mechanism (or Cause)	Local Effect	Global Effect	Hidden / Evident Failure	Dangerous Failure	Failure Development	Maintenance Task	Maintenance Interval	Inspection task	Inspection interval	
Substructure of floating wind turbine	Mooring system	Mooring lines	Abnormal mooring line	Mooring lines wear Moring lines fatigue Mooring lines corrosion Abnormal stress Not effective maintenance	Mooring line strength decrease or broken	Plant shutdown, loss of position control, reduced stability	Yes	Yes	Aging	Replace	When required	General Visual Inspection (GVI)	5Y	Bureau Veritas-NR 493 DT R03 E
			Mooring lines broken	Traditional chain wear Friction chain wear Mooring winch failure Buoys friction chain wear anchor pickup device damage Hydraulic motor failure Accumulator failure Overpressure Connectors failure Mooring interface structure failure	Malfunction of the whole system, the FOWT cannot locate in the water	Plant shutdown, loss of position control, reduced stability	Yes	Yes	Aging	Replace	When required	General Visual Inspection (GVI)	5Y	Bureau Veritas-NR 493 DT R03 E
Substructure of floating wind turbine	Mooring system	Fairlead	Fairlead failure	Fairlead corrosion Fairlead fatigue	The anchor cannot be dropped and lift	No need for shutdown, need immediately maintenance	Yes	No	Aging	Replace, Repair	When required	Detailed Visual Inspection (DVI)	Within 1Y from start of operation (damage inspection). Additional inspections to be determined if significant changes found after this first inspection. Interval shall not exceed 5Y.	Bureau Veritas-NR 493 DT R03 E
Substructure of floating wind turbine	Mooring system	Anchor	Anchor failure	Abnormal working conditions Cyclic degradation	Detaches from seabed	Plant shutdown, loss of position control	Yes	Yes	Aging	Replace, Repair	When required	Detailed Visual Inspection (DVI)	Within 1Y from start of operation (damage inspection). Additional inspections to be determined if significant changes found after this first inspection. Interval shall not exceed 5Y.	DNV GL-SE-0422
Substructure of floating wind turbine	Floating Foundation	Brace structure	Watertight fault, broken braces	Inefficient detection Pipe joint corrosion Pipe joint weld defect Pipe joint fatigue Erosion Breakage	increased water level in bracestructure, leads to increased weight, increased stresses on structure	No need for shutdown, need immediately maintenance	Yes	No	Aging	Repair	When required	General Visual Inspection (GVI)	5Y	DNVGL-ST-0119, in consideration of DNVGL-ST-0126
Substructure of floating wind turbine	Floating Foundation	Pontoons and columns	Watertight fault	Inefficient detection Corrosion Fatigue Weld failures	increased water level in pontoons and columns, increased weight, and unstable structure because of different water levels.	Plant shutdown	Yes	Yes	Aging	Repair	When required	General Visual Inspection (GVI)	5Y	DNVGL-ST-0119, in consideration of DNVGL-ST-0126
Substructure of floating wind turbine	Electrical	Dynamic cables	Dynamic cables failure	Fatigue Fishing activity Overheating Corrosion Marine growth Cuts on cable	No power or communication to plant	Plant shutdown	Yes	No	Aging	Replace, Repair	When required	First inspection as an "as-laid inspection", then GVI on later inspections.	Within 1Y from start of operation (damage inspection). Additional inspections to be determined if significant changes found after this first inspection. Interval shall not exceed 5Y.	DNVGL-RP-0360

Table 8 - FMECA of semi-submersible FOWT

To decide what maintenance task to do, ISO-14224-Appendix-B [23] and Marvin Rausand [27] has been used as references. It contains a table of the different maintenance tasks that are possible to perform and examples of when each of them is used. As presented in the table above, the maintenance task that are recommended for our system and the different units is replace or repair. Because of the environmental conditions that the FOWT is in it is often difficult to perform different maintenance task, which means that if maintenance is needed, replacing, or repairing the maintainable unit is the best option. Performing maintenance at sea is also expensive, which means that the maintenance task must be as cost-effective as possible. In the FMECA (table 8 & 9), it has been suggested for fairlead, anchors, and dynamic cables that they can be either replaced or repaired depending on what failure that has occurred. In touch with experts on mooring system from Equinor [18], it has been discussed what the best solution for the mooring lines is. The conclusion is that to replace the whole mooring line or parts of it is the best option based on the difficulty and environmental conditions, but it also depends on what the failure is and how comprehensive it is.

For the maintenance interval it is suggested that it should be when required, if the inspections detects that it is need for maintenance, then maintenance should be ordered. To have maintenance on this system each year is not very cost-effective and therefore it is better to have good monitoring of the system and then only do maintenance when it is required.

To monitor and detect failures in the system, regular inspections must be done. The suggested inspections tasks are GVI (General Visual Inspection) and DVI (Detailed Visual Inspection). The scope of the GVI is to assess damage on structure, general wear on chain links, corrosion, missing or loose parts and distorted elements. This can be done by either a ROV or a diver, but because of the HSE risk of diving in these conditions and the matured ROV technology, ROV is the best option. If GVI detects something unusual, it can be required an DVI to get a more detailed inspection of the system. The scope of a DVI is to assess material degradation, conditions of issues from GVI, corrosion, pitting, cracks, and indications of weld defects. In the FMECA (table 8 & 9), it has only been suggested DVI on fairlead and anchors. This is because of the environmental conditions that they are in, fairleads are located around the splash zone, which is the area with the most corrosion, and anchors is at seabed where it is bad sight and therefore it is need for a more detailed view.

The FOWTs (Floating Offshore Wind Turbine) need regular inspections, and the intervals that are recommended in the FMECA (table 8 &9) is 5-year intervals. This is suggested by both DNV (Det Norske Veritas) and Bureau Veritas. For the anchors, fairleads, and dynamic cables it is recommended that within 1-year from start of operation it is necessary to do inspections to check conditions and how things have developed. After this first year inspection is done it should be discussed how often the next intervals shall be, but as said earlier, it should never exceed 5-years.

The FMECA only presents what inspection task to do and when to do it, therefore it has been developed an own inspection plan (table-10) with information about what to inspect, where to inspect, how to inspect, difficulties with inspection and which ROV type that is recommended for the inspection. Next subchapter will also discuss which of Oceaneering's ROVs that suit for each inspection and if it is more effective to perform the inspections at the OROC where the ROVs are being remotely controlled from onshore.

4.3 Inspection of the semi-submersible FOWT

For a FOWT to sustain the impact from the environment and operations during the lifetime it is necessary with sufficient inspections and maintenance. This section will discuss how the semi-submersible FOWT shall be inspected and suggest suitable method for the various parts of the FOWT using Oceaneering's ROVs.

For sufficient suggestion for inspection methods, it is crucial to consider several factors. It is important to identify what to inspect, where to inspect and how to inspect. This is to highlight what operation needs to be performed and how to do it. Another crucial factor for suggesting inspection method and what ROV to use is to look at the difficulties with the inspection. The ROVs has different properties that is suitable for solving difficulties. An outline table has been set up to highlight these factors and suggested type of ROV to use. The FMECA in table 8 & 9 comments on interval for inspection and maintenance.

	What to inspect for (failure mechanisms)	Where to inspect (equipment)	How to inspect (method)	Difficulties with inspection	ROV type
	Mooring lines (1st annual)				
General inspection covers corrosion, damages, deformation, cracks, abrasions, dents, wear etc. which gives an overview over the conditions. DVI=Detailed Visual Inspection	General inspection	All over mooring system	Visual, DVI if necessary	Movement in mooring line	Freedom for visual inspection only, Liberty E-ROV or Isurus if need of work class ROV
	Marine growth	Top of mooring line	Visual inspection	Movement in mooring line	
	Twist in chain/wire	Selected areas of mooring line	Visual inspection	Movement in mooring line, visibility to see twist over number of links	
	Alingment of chain in fairleads	Fairleads	Visual inspection	Movement in mooring line, shallow water depth	
	Trenches in proximity to anchors	Seabed close to anchors	Visual inspection	Movement in mooring line, visibility	
	Misalignments in connections of mooring line	Connections of mooring line	Visual inspection	Movement in mooring line	
	Interlink wear on chains	Selected interlinks on chain	Visual inspection	Movement in mooring line	
	Mooring lines (5 years annual)				
	General inspection	All over mooring system	Visual inspection, Clean and DVI if necessary	Need to clean mooring line, Movement in mooring line	Liberty E-ROV, Isurus is recommended if harsh weather conditions at wind farm.
	Marine growth (extent and type)	All over mooring line	Visual inspection, clean if necessary	Movement	
	Wear and tear, mismatch between chain links and fairlead pockets, twist beetween upper/lower fairleads	Fairleads, chain in fairleads	Visual inspection	Movement, shallow water depth	
	Wear, plane bending, free movement	Fairleads, chain in fairleads	DVI	Movement, shallow water depth	
	Diameter chain links	Every 100th link for general chain	Measurements for diameter	Movement	
	Diameter chain links	Every link for chain in spalsh zone	Measurements for diameter	Movement	
	Wear and scouring	Chain touchdown area (seabed)	Clean, DVI, measurements of scouring	Movement, visibility	
	Wire breaks, fractures, rope diameter, wear and corrosion, deformation	Wire rope	DVI, measurements of corrosion rate and diameters	Movement	
	Trenches in proximity to anchors	Anchor area	Visual inspection	Movement, visibility	
	Wear, twist or other damages	Connectors, shackles, sockets etc	DVI	Movement	
	Floater hull				
	General inspection	All over floating hull	Visual inspection	Shallow water depth	Liberty E-ROV, Isurus is recommended if harsh weather conditions at wind farm.
	Marine growth (extent and type)	All over floating hull	Visual inspection	Shallow water depth	
	Corrosion	All over floating hull	DVI, measurements of corrosion rate	Shallow water depth	
	Dents, deformations	All over floating hull	DVI	Shallow water depth	
	Damage, worn out	Corrosion protection systems	DVI	Shallow water depth	
	Dynamic cable				
	General inspection	All over dynamic cable	Visual inspection	Need to clean cable, movement of cable	Liberty E-ROV, Isurus is recommended if harsh weather conditions at wind farm.
	Marine growth (extent and type)	All over cable, floating elements	Visual inspection, clean if needed	Movement of cable	
	Functionality and condition	Cable supports and guides	Visual inspection	Visibility, shallow depth	

Table 9 – A detailed inspection plan including use of Oceaneering's ROVs based on DNVGL-RU-OU-0300 [9] and Corewind D4.1 [22]

The operations for inspections of the semi-submersible FOWT takes all the parts in consideration, the mooring system, the floater hull, and the dynamic cable. Inspection for mooring system shall cover anchors, wire, chain, fairleads, and connectors. The floater hull shall cover external shell, compartments, and corrosion protection systems (anodes). [9] For the dynamic cable the floating elements, the cable and the support structures shall be covered. [8]

What to inspect is quite similar for all the parts where the crucial factors are to identify failure profiles and to state the conditions of the equipment. All parts require a general inspection which covers corrosion, damages, deformation, cracks, abrasions, dents, wear etc. which gives an overview over the conditions.

The mooring line and the dynamic cable require an inspection within a year after installation when the system has settled. This is a visual inspection to identify any problems with the system, and to create a baseline for future inspections. The inspection for the mooring line covers all parts from anchors to fairleads. The visual inspections shall cover a general inspection and ensure the lines are in correct alignment in the fairleads and has no twists in general. Area around the anchors should also be inspected to identify trenches or other failures with the anchors. These inspections are visual and primarily there is no need for work class ROVs.

Annual inspections shall not exceed 5 years and shall cover the mooring system, the floater hull, and the dynamic cable. These inspections are in addition to the inspections described and performed for the 1st annual and shall be more critical and cover more detailed parts. The critical parts shall receive a DVI (Detailed Visual Inspection) where all deviations for parts shall be located. This can be corrosion, damages, wear, deformations, etc. The results may lead to further actions with NDT (Non-Destructive Testing) or measurements. Areas where corrosion is located shall be measured and monitored in future inspections to identify the rate of corrosion. Areas with damages like bending, dents or deformation shall have NDT performed. Another work needed to perform for the parts is cleaning if there is identified a significant extent of marine growth. These annual 5 years inspections require work class ROVs. [9]

Difficulties with inspections might be the deciding factor for selection of inspection method and ROV to use. Inspection at shallow water depths is challenging due to waves and the waterflow makes it difficult for ROVs to maintain position. Movement in the various parts is also a challenge for inspection due to difficulties for ROVs to follow the movement. Other difficulties could be sufficient visibility due to lack of light, dirty water, or marine growth at the parts.

4.4 Selection of ROV

For selection of ROV several factors must be consider as mentioned above. The ROV is categorized for what work they are going to do. Some are built for inspection, and some are built for work. Earlier in the report, Oceaneering's next generation subsea vehicles have been presented. These are the Isurus, Liberty E-ROV and Freedom AUV. In touch with Oceaneering's ROV team, it has been discussed what these different ROVs can contribute with in the FOWT industry. Both Isurus and Liberty E-ROV is work class ROVs, and on the other hand the Freedom is an autonomous underwater vehicle (AUV) which is better for pipeline surveys. The Isurus and Liberty have abilities that suit inspection tasks presented above, still the Freedom might be beneficial for visual inspections.

Earlier in the report it has been presented pros and cons with Isurus, Liberty and Freedom. The Isurus can handle tough weather conditions and it can achieve high speed which reduce operation time. On the other hand, the Liberty E-ROV reduces carbon footprint and mobilizations because of the battery package, it can reduce vessel days required to complete operations and it can take advantage of favorable weather windows faster. The Freedom can be used for visual inspection where a work class ROV is not needed. All ROVs can also be remotely controlled from the OROC.

After considering all types and considering the contribution to reduce CO2 emissions the recommended ROV for a semi-submersible FOWT is the Liberty E-ROV. On some occasions Isurus may be the better fit due to weather conditions and is therefore recommended as an option if extreme conditions at and around the windfarm. For 1st annual inspection, which is only visual, the Freedom can be beneficial.

5. Conclusion

The thesis presents a literary study of the semi-submersible FOWT in the scope of inspection & maintenance planning. The study includes an RCM program, which presents risks, criticality, failures, failure effects, maintenance interval, maintenance task, inspection interval, inspection task and more on each maintainable unit through an FFA and FMECA which is attached to this thesis. The use of Oceaneering's next generation subsea vehicles to inspect the semi-sub has also been discussed.

Since the offshore wind industry is new, it is expected that this first RCM program will not be perfect. Some failure modes may be overlooked or others that it is unlikely to happen can have been included in the analysis. This is one of the reasons that many experts and specialists call RCM as a living program, that must be reviewed and updated regularly.

For the semi-submersible FOWT, it is the mooring system with mooring lines, anchors and fairleads that shows to be the most critical parts, but also the pontoons and columns from the floating foundation. To prevent these critical parts from failure, a specific inspection & maintenance plan has been developed.

The inspection is important to be able to detect failures, and to perform inspections on the semi-submersible, Oceaneering's Liberty E-ROV is recommended due to its features that suits for this kind of work. Although the Isurus is more preferred in extreme weather conditions and the Freedom can be used for visual inspection only.

In conclusion, the most critical parts of a semi-submersible FOWT have been highlighted, and a more specific inspection plan with recommendations of which of Oceaneering's next generation ROVs to use have been developed.

6. Recommendations for further work

This thesis covers an RCM program for the substructure of a floating wind turbine and suggestions for inspection with the use of ROVs. Since this is a bachelor thesis the amount of time available for working with the project has been limited. Therefore, limitations had to be set to narrow the scope of work.

The floating offshore wind industry is relatively new and in constant development. Therefore, it is recommended to regularly update the content in the RCM program for the semi-submersible FOWT. There is no assurance for the semi-submersible structure to be the preferred design, so comparison with other current structures would be recommended. Further work should also consider how the structure will be suitable for and affected by different offshore sites. Selection of ROV will also be affected by the conditions, like depths and environment, at the various sites.

Remote operation can be a beneficial method for operation of ROVs on offshore wind locations. It is recommended to look at possibilities to implement this method and look at economical costs compared to traditional ways for operating ROVs. It is also important to consider availability of relevant types of ROVs.

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Attachment 1

System	Subsystem	Maintainable Unit / Part	Functions	Failure Effect	Probability of Failure	Consequence of Failure (Safety)	Consequence of Failure (Safety) - Notes	Consequence of Failure (Environmental)	Consequence of Failure (Environmental) - Notes	Consequence of Failure (Economic)	Consequence of Failure (Economic) - Notes	Risk (Safety)	Risk (Environmental)	Risk (Economic)	Critical / Noncritical
Substructure of floating wind turbine	Mooring system	Mooring lines	Keep the structure in place, take loads from environment (currents, winds, and waves)	Malfunction of whole system, the FOWT cannot locate in water	2 - Low	C - Major Injury	Danger for vessels nearby, and possible inspection & maintenance personnell	B - Minor Pollution	Minor pollution, no danger of chemical leaks	E - Massive Loss	Big economic loss, due to damage and cost of operations to get the turbine up and running	3 - Medium	2 - Low	4 - High	Critical
Substructure of floating wind turbine	Mooring system	Anchors	Secure the wind turbine to seafloor	anchor failure, detaches from the seabed	2 - Low	C - Major Injury	Danger for vessels nearby, and possible inspection & maintenance personnell	C - Moderate Pollution	Moderate pollution, no danger of chemical leaks, material leaks can occur, muddy sea	E - Massive Loss	Big economic loss, due to damage and cost of operations to get the turbine up and running	3 - Medium	2 - Low	4 - High	Critical
Substructure of floating wind turbine	Mooring system	Fairlead	guide the mooring lines and anchor, drop and lift	Anchor and mooring lines cannot be dropped and lift	3 - Medium	B - Minor Injury	Minor damage will occurr, no danger for nearby vessels	C - Moderate Pollution	Moderate pollution, no danger of chemical leaks, material leaks can occur	C - Moderate Loss	Moderate economic loss, not a major part of the FOWTs function	3 - Medium	3 - Medium	3 - Medium	Critical
Substructure of floating wind turbine	Electrical	Dynamic cables	Deliver power/communication to the FOWT, and send power/communication onshore	No communication and power to the wind turbine	2 - Low	A - No Injury	No damage will occurr to nearby vessels or possible inspection & maintenance personnel	C - Moderate Pollution	Moderate pollution, no danger of chemical leaks, material leaks can occur	D - Major Loss	Major economic loss, due to damage on electrical and time to fix	1 - Very Low	3 - Medium	3 - Medium	Noncritical
Substructure of floating wind turbine	Floating Foundation	Pontoons and columns	Make the FOWT float and makes it very stable	Unstable structure, which can lead to capsizing	2 - Low	E - Multiple Fatality	Hazardous. If personnel on board, death may occur. Can damage nearby vessels with people onboard	D - Major Pollution	Major pollution if capsizing, chemical leaks and material leaks(plastic etc.)	E - Massive Loss	Big economic loss, due to damage and cost of operations to get the turbine up and running	4 - High	3 - Medium	4 - High	Critical
Substructure of floating wind turbine	Floating Foundation	Braces between pontoons and columns	keep the structure stable	can lead to more strain/stress on other components, which make it more unstable and lead to other failures	2 - Low	B - Minor Injury	Minor damage will occurr, no danger for nearby vessels	A - Slight Pollution	Slight pollution, no chemical leaks	D - Major Loss	Major economic loss, due to damage on braces and time to fix	2 - Low	1 - Very Low	3 - Medium	Noncritical

Attachment 2

Number			Failure Mode & Mechanism		Effect					Maintenance Planning		Inspection Planning		Reference
System	Subsystem	Maintainable Unit	Failure Mode	Failure Mechanism (or Cause)	Local Effect	Global Effect	Hidden / Evident Failure	Dangerous Failure	Failure Development	Maintenance Task	Maintenance Interval	Inspection task	Inspection interval	
Substructure of floating wind turbine	Mooring system	Mooring lines	Abnormal mooring line	Mooring lines wear Moring lines fatigue Mooring lines corrosion Abnormal stress Not effective maintenance	Mooring line strength decrease or broken	Plant shutdown, loss of position control, reduced stability	Yes	Yes	Aging	Replace	When required	General Visual Inspection (GVI)	5Y	Bureau Veritas-NR 493 DT R03 E
			Mooring lines broken	Traditional chain wear Friction chain wear Mooring winch failure Buoys friction chain wear anchor pickup device damage Hydraulic motor failure Accumulator failure Overpressure Connectors failure Mooring interface structure failure	Malfunction of the whole system, the FOWT cannot locate in the water	Plant shutdown, loss of position control, reduced stability	Yes	Yes	Aging	Replace	When required	General Visual Inspection (GVI)	5Y	Bureau Veritas-NR 493 DT R03 E
Substructure of floating wind turbine	Mooring system	Fairlead	Fairlead failure	Fairlead corrosion Fairlead fatigue	The anchor cannot be dropped and lift	No need for shutdown, need immediately maintenance	Yes	No	Aging	Replace, Repair	When required	Detailed Visual Inspection (DVI)	Within 1Y from start of operation (damage inspection). Additional inspections to be determined if significant changes found after this first inspection. Interval shall not exceed 5Y.	Bureau Veritas-NR 493 DT R03 E
Substructure of floating wind turbine	Mooring system	Anchor	Anchor failure	Abnormal working conditrions Cyclic degredation	Detaches from seabed	Plant shutdown, loss of position control	Yes	Yes	Aging	Replace, Repair	When required	Detailed Visual Inspection (DVI)	Within 1Y from start of operation (damage inspection). Additional inspections to be determined if significant changes found after this first inspection. Interval shall not exceed 5Y.	DNV GL-SE-0422
Substructure of floating wind turbine	Floating Foundation	Brace structure	Watertight fault, broken braces	Inefficient detection Pipe joint corrosion Pipe joint weld defect Pipe joint fatigue Erosion Breakage	increased water level in bracestructure, leads to increased weight, increased stresses on structure	No need for shutdown, need immediately maintenance	Yes	No	Aging	Repair	When required	General Visual Inspection (GVI)	5Y	DNVGL-ST-0119, in consideration of DNVGL-ST-0126
Substructure of floating wind turbine	Floating Foundation	Pontoons and columns	Watertight fault	Inefficient detection Corrosion Fatigue Weld failures	increased water level in pontoons and columns, increased weight, and unstable structure because of different water levels.	Plant shutdown	Yes	Yes	Aging	Repair	When required	General Visual Inspection (GVI)	5Y	DNVGL-ST-0119, in consideration of DNVGL-ST-0126
Substructure of floating wind turbine	Electrical	Dynamic cables	Dynamic cables failure	Fatigue Fishing activity Overheating Corrosion Marine growth Cuts on cable	No power or communication to plant	Plant shutdown	Yes	No	Aging	Replace, Repair	When required	First inspection as an "as-laid inspection", then GVI on later inspections.	Within 1Y from start of operation (damage inspection). Additional inspections to be determined if significant changes found after this first inspection. Interval shall not exceed 5Y.	DNVGL-RP-0360

Attachment 3

General inspection covers corrosion, damages, deformation, cracks, abrasions, dents, wear etc. which gives an overview over the conditions. DVI=Detailed Visual Inspection

What to inspect for (failure mechanisms)	Where to inspect (equipment)	How to inspect (method)	Difficulties with inspection	ROV type
Mooring lines (1st annual)				
General inspection	All over mooring system	Visual, DVI if necessary	Movement in mooring line	Freedom for visual inspection only, Liberty E-ROV or Isurus if need of work class ROV
Marine growth	Top of mooring line	Visual inspection	Movement in mooring line	
Twist in chain/wire	Selected areas of mooring line	Visual inspection	Movement in mooring line, visibility to see twist over number of links	
Alingment of chain in fairleads	Fairleads	Visual inspection	Movement in mooring line, shallow water depth	
Trenches in proximity to anchors	Seabed close to anchors	Visual inspection	Movement in mooring line, visibility	
Misalignments in connections of mooring line	Connections of mooring line	Visual inspection	Movement in mooring line	
Interlink wear on chains	Selected interlinks on chain	Visual inspection	Movement in mooring line	
Mooring lines (5 years annual)				
General inspection	All over mooring system	Visual inspection, Clean and DVI if necessary	Need to clean mooring line, Movement in mooring line	Liberty E-ROV, Isurus is recommended if harsh weather conditions at wind farm.
Marine growth (extent and type)	All over mooring line	Visual inspection, clean if necessary	Movement	
Wear and tear, mismatch between chain links and fairlead pockets, twist beetween upper/lower fairleads	Fairleads, chain in fairleads	Visual inspection	Movement, shallow water depth	
Wear, plane bending, free movement	Fairleads, chain in fairleads	DVI	Movement, shallow water depth	
Diameter chain links	Every 100th link for general chain	Measurements for diameter	Movement	
Diameter chain links	Every link for chain in spalsh zone	Measurements for diameter	Movement	
Wear and scouring	Chain touchdown area (seabed)	Clean, DVI, measurements of scouring	Movement, visibility	
Wire breaks, fractures, rope diameter, wear and corrosion, deformation	Wire rope	DVI, measurements of corrosion rate and diameters	Movement	
Trenches in proximity to anchors	Anchor area	Visual inspection	Movement, visibility	
Wear, twist or other damages	Connectors, shackles, sockets etc	DVI	Movement	
Floater hull				
General inspection	All over floating hull	Visual inspection	Shallow water depth	Liberty E-ROV, Isurus is recommended if harsh weather conditions at wind farm.
Marine growth (extent and type)	All over floating hull	Visual inspection	Shallow water depth	
Corrosion	All over floating hull	DVI, measurements of corrosion rate	Shallow water depth	
Dents, deformations	All over floating hull	DVI	Shallow water depth	
Damage, worn out	Corrosion protection systems	DVI	Shallow water depth	
Dynamic cable				
General inspection	All over dynamic cable	Visual inspection	Need to clean cable, movement of cable	Liberty E-ROV, Isurus is recommended if harsh weather conditions at wind farm.
Marine growth (extent and type)	All over cable, floating elements	Visual inspection, clean if needed	Movement of cable	
Functionality and condition	Cable supports and guides	Visual inspection	Visibility, shallow water depth	

Attachment 4

		CoF Ranking				
CoF - Environmental		A - Slight Pollution	B - Minor Pollution	C - Moderate Pollution	D - Major Pollution	E - Massive Pollution
CoF - Economical		A - Slight Damage	B - Minor Damage	C - Moderate Damage	D - Major Damage	E - Massive Damage
CoF - Economical		A - Slight Loss	B - Minor Loss	C - Moderate Loss	D - Major Loss	E - Massive Loss
CoF - Safety		A - No Injury	B - Minor Injury	C - Major Injury	D - Single Fatality	E - Mulitple Fatality
PoF Ranking	5 - Expected	3 - Medium	4 - High	4 - High	5 - Very High	5 - Very High
	4 - High	3 - Medium	3 - Medium	4 - High	4 - High	5 - Very High
	3 - Medium	2 - Low	3 - Medium	3 - Medium	4 - High	4 - High
	2 - Low	1 - Very Low	2 - Low	3 - Medium	3 - Medium	4 - High
	1 - Negligible	1 - Very Low	1 - Very Low	2 - Low	3 - Medium	3 - Medium

CoF - Safety	No Injury	Minor injuries, with short recovery time	Injuries, with some recovery time	Serious injury with longer recovery time	Irreversible or fatal injury.
CoF - Safety	No Injury	Minor cuts, falling and getting a few scratches	Cuts that might need stitches, sprained ankles	Significant cuts, broken arms or legs	Serious head trauma, drowning
PoF	Rarely	Unikely	Possibly	Likely	Almost Certainly