Application of ISO 55000 to develop a maintenance strategy for Odfjell Oceanwind's wind turbine

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Høgskulen på Vestlandet

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Preface

This thesis is written by three students in the Department of Mechanical engineering and Maritime studies at the Western Norwegian University of Applied Sciences (HVL) at the Bergen, Norway campus. The thesis is written in collaboration with Odfjell Technology.

In Norway, the development of offshore wind is something that is fast growing and gets a lot of resources. This is something that requires new technology and innovative solutions. One significant advantage of this development in Norway is the possibility to utilize over 50 years of experience gained from the oil sector.

We would like to thank Alexander Hatland and Heidi Eftestøl for invaluable guidance during this project. They have also provided us with all the documents needed and welcomed us into the office. This was very helpful and made us get a close insight into how the industry function. During our time with Odfjell Technology at Kokstadflaten, Bergen, Hatland and Eftestøl also played a crucial role in the set up of the interviews.

We would also like to thank our supervisor, Professor Maneesh Singh, for providing valuable academic guidance in the development of this bachelor thesis. This guidance made us gather crucial knowledge regarding asset management.

Finally, thanks to Tone Røkenes for the method course, and the library at HVL for providing the resources needed.

odfjell technology

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Abstract

Odfjell Oceanwind are planning to develop a wind farm in the Barents Sea called GoliatVIND. This thesis applies the ISO 55000 standards, a standard on asset management, to develop a maintenance strategy for GoliatVIND. The strategy is structured from the sections of the standards, and the methods are sorted in the relevant section.

A summary of ISO 55000 is presented as well as a overview of a generic semi submersible wind turbine.

Interview with personnel from Odfjell Oceanwind and Odfjell Technology is executed. The purpose of the interview is to discover the necessities for the maintenance strategy for Odfjell Oceanwind's wind turbines. The questions in the interview are based upon ISO 55000.

The maintenance strategy has a reliability centered maintenance based approach with a condition monitoring system as a portion of the input data. The strategy addresses issues regarding CMMS, logistics etc.

Sammendrag

Odfjell Oceanwind planlegger å utvikle vind farmer i Barentshavet, kalla GoliatVIND. Prosjektet anvender standarden ISO 55000, som omhandler essursstyring. Dette blir benyttet for å strukturere og konstruere vedlikeholdsstrategi for GoliatVIND. De ulike delene av vedlikeholdsstrategien blir sortert under dei passende kapitlene av standarden.

En oppsummering av ISO 55000 blir presentert i rapporten, i tillegg til en generell modell og teoridel av en halvt-nedsenkbar vind turbin.

I prosjektet blir det utført intervju med personell fra Odfjell Oceanwind og Odfjell Technology. Formålet med disse intervjuene er å finne ut hva som er nødvendig og ønskelig i vedlikeholdsstrategien for Odfjell Oceanwind's vindturbiner. Spørsmålene baserer seg på ISO 55000.

Vedlikeholdsstrategien har pålitelighetssentrert vedlikehold som tilnærming. I tilnærmingen blir tilstandsovervåkning vektlagt. Strategien tar opp utfordringer angående CMMS, logistikk, osv.

Contents

1 Introduction

This chapter will provide information about the company, motivation for the thesis, aim and scope, in addition to definitions and abbreviations used in the project.

1.1 Odfjell Technology

In 2021 Odfjell Drilling (ODL) was divided into two sub companies; Odfjell Technology LTD (OTL) and Odfjell Drilling LTD. OTL is an integrated supplier of offshore operations, well services technology and engineering solutions.[1]

They are divided into three divisions; Projects & Engineering, Operations and Well Services. Projects & Engineering does modifications & upgrades, compliance services, integrity services, and energy optimization & emissions reduction. OTL have over 50 years' experience and are operating in 30 countries. They have drilling contracts on 16 floating and fixed platforms in addition to one Jack-Up rig. [2]

1.2 Odfjell Oceanwind

In 2020 Odfjell invested in Oceanwind and renamed it Odfjell Oceanwind (OOW). OOW is currently a private company with strong ties to OTL and ODL. The aim of the company is to make floating wind solutions as simple as possible, using experience from developing offshore drilling units. [3]

1.3 Motivation

Offshore wind turbines are a hot topic in the question of renewable energy sources. The thesis was given from OTL, who has 50 years of experience in the offshore industry. OTL has strong connections with OOW who are planning several offshore wind turbines, that OTL wishes to execute the maintenance for. While there are many solutions to the maintenance of offshore wind turbines already, OOW has not yet started operating and needs a maintenance strategy.

1.4 Aim of the project

The aim of the project is to develop an asset integrity maintenance strategy for an offshore wind turbine using ISO55000 for Odfjell Technology LTD.

1.5 Scope

The scope of the thesis is:

- Gather an understanding of the working structures and components of semi-submersible wind turbines and an understanding of ISO 55000
- Follow standards and regulations used for offshore wind installations and maintenance for offshore industries.
- Develop a maintenance strategy for OOW's offshore wind turbines according to ISO 55000.

1.6 Limitations

Since OOW is an independent company, our resources will depend on what they can share outside the company. Because of limited time resources individual research will not be done, and the thesis will be based on existing research. There are several up-to-date research papers that can be applied to this task. ISO 55000 will not be applied in full detail in the interviews. This applies for the results as well.

1.7 Structure

The thesis is divided into 9 chapters and 1 appendix. Below is an overview:

- Chapter 1: Introduction
- Chapter 2: Theory
- Chapter 3: Summary of ISO55000
- Chapter 4: Methodology
- Chapter 5: Interview
- Chapter 6: Results
- Chapter 7: Recommendations
- Chapter 8: Discussion
- Chapter 9: Conclusion
- Appendix A: Drawings

1.8 Abbreviations

AC:	Alternating current
AI:	Artificial Intelligence
AIM:	Asset Integrity Management
AM:	Asset Management
AMS:	Asset Management System
API:	Application Programming Interface
BMS:	Blade monitoring System
CBM:	Condition based maintenance
CM:	Corrective maintenance
CMMS:	Computerized maintenance management system
CMS:	Condition monitoring systems
DC:	Direct current
DNV:	Det Norske Veritas
EAM:	Enterprise asset management
ERP:	Enterprise resource planning
FFA:	Function failure analysis
FMECA:	Failure mode, effects, and criticality analysis
FOWU:	Floating offshore unit
HMI:	Human machine interface
IEC:	International Electrotechnical Commission
ISO:	International Organization for Standardization
MDT:	Mean downtime
MTTF:	Mean time to failure
MTTR:	Mean time to repair
MTBF:	Mean time between failure
NORSOK:	NORsk SOkkels Konkurranseposisjon
O&M:	Operations and maintenance
ODL:	Odfjell Drilling
OEM:	Original equipment manufacturer

OOW: Odfjell Oceanwind

OTL: Odfjell Technology

PLC: Programmable logical controller

PM: Preventative maintenance

PO: Purchase orders

RCM: Reliability centered maintenance

RTU: Remote terminal unit

SCADA: Supervisory Control and Data Acquisition

WTG: Wind turbine generator

WT: Wind turbine

1.9 Definitions

Availability: The ability of an item to perform its required function at a stated instant of time or over a stated period of time[4, p. 367]

Asset: An item thing or entity that has potential or actual value to an organization [5, p. 13].

Asset management: Coordinated activity of an organization to realize value from assets[5, p. 14]

Life cycle: Stages involved in the management of an asset[5, p. 13]

Maintenance plan: Structured and documented set of tasks required to carry out the maintenance [6, p. 5]

Maintenance strategy: Maintenance method used to achieve the maintenance objectives [6, p. 5]

Maintenance objective: Target assigned and accepted for the maintenance activities [6, p. 5]

Nonconformity: Non-fulfilment of a requirement[5, p. 11]

Preventive action: Action to eliminate the cause of a potential nonconformity or other undesirable potential situation[5, p. 14]

Predictive action: Action to monitor the condition of an asset and predict the need for preventive action or corrective action [5, p. 15]

Risk: Effect of uncertainty on objectives[5, p. 12]

Stakeholder: Person or organization that can affect, be affected by, or perceive themselves to be affected by a decision or activity[5, p. 12]

2 Theory

2.1 Semi submersible wind turbines

The structure of offshore a windturbine (WT) consists of two parts; the superstructure (topside) and the substructure (subsea). Below is a general description of the structure of the semi-submersible WT.

2.1.1 Topside

To get an overview of the different parts of the topside of the WT, a technical hierarchy was developed. This is shown in figure 2 :

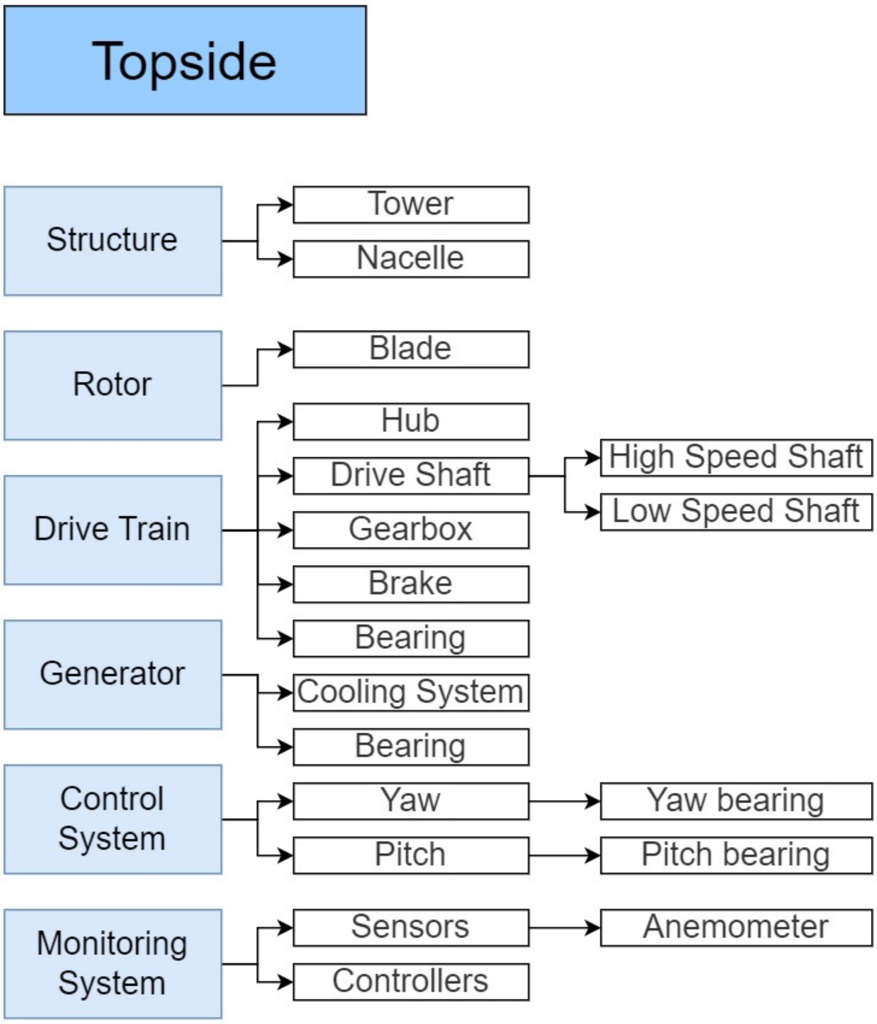

Figure 2: Technical hierarchy for the topside of an offshore wind turbine

The WT in this thesis is a horizontal axis WT, which means that the rotor turns around the horizontal axis. [7, p. 19-20]

Figure 3: Simplified version of the offshore wind turbine; topside. Based on [8].

The topside of the WT consists of the tower with a nacelle mounted on top, with a large bearing which is located between the two components. The bearing allows the whole drive train to turn so that the rotor of the WT is facing the wind.[7, p. 21-23]

The tower height must be tall enough for the blades to not hit the ground, or other obstacles. The drawing in appendix A shows typical dimensions of a WT. The wind speed is higher the further up the turbine is placed. This is because the turbulence that occurs closer to the ground will not affect the turbine in the same degree higher up.[7, p. 12-14]

The nacelle houses the components of the drive train and protects them from wear. It needs to be lightweight, yet capable of bearing a significant amount of weight. The nacelle is mounted onto a large bearing, on top of the tower. [7, p. 25-26]

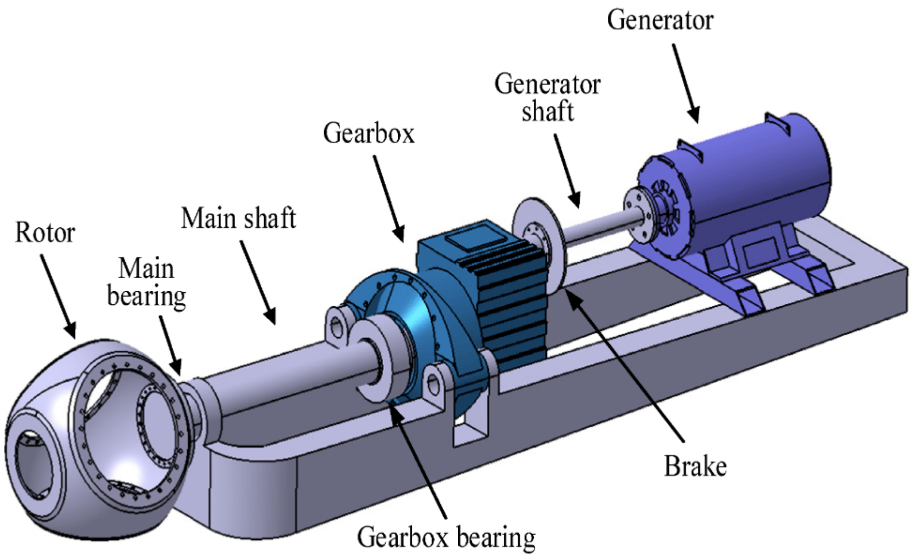

Figure 4: Example of drive train [9]

The components in the drive train are the drive shafts, the generator, and a brake. The brake is used to prevent the rotor from rotating in very low or high wind speed. There is also a range of hydraulic and servo systems that control the blade pitch, the rotor speed, and the orientation of the nacelle structure. If the WT is not direct drive but geared, the gearbox is also a part of the drive train. In modern WT there will also be a real-time condition monitoring system (CMS) in the nacelle. A example of a drive train is shown in figure 4. [7, p. 51]

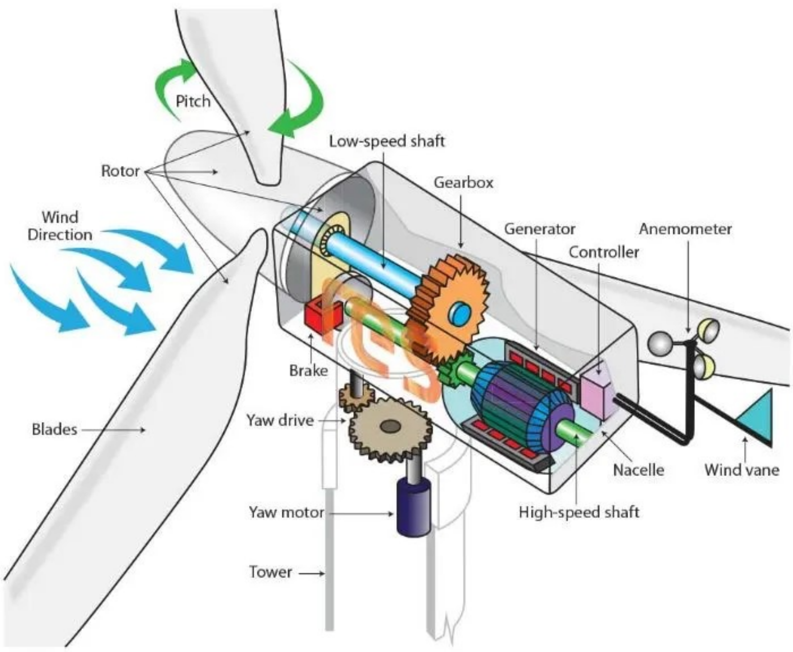

Figure 5: Components in nacelle [10]

The weakest link in the drive train of a WT is often considered to be the gearbox. It needs to withstand a variety of shocks and load that are uncommon in typical gearbox applications. An alternative for the

gearbox is direct drive. With a direct drive system, the hub is directly connected to the generator. The system can provide a greater reliability but for the system to turn at higher speeds a lot of poles are required. The current issue with direct drive is the large size of the generator that are needed for larger capacities.[7, p. 41-44]
The horizontal axis WT has a rotor, consisting of blades and a rotor hub. The standard WT has a rotor with three blades. The rotor on the WT captures the energy from the wind. The energy is transferred from the rotor to the WT shaft as a rotational motion. This rotational motion is converted into electrical energy by a generator. The blades of the WT have an aerofoil cross-section to create lift. [7, p. 31]
The generator converts mechanical rotary energy into electrical energy [7, p. 44-48]. There are different types of generators. These are listed below:

- Doubly-fed induction generators
- Synchronous generators
- Direct drive generators

[7, p. 44-48]

It is important to keep the WT at the direction towards the wind. This is done by monitoring signals form the wind vane, which checks the wind direction. The data from the signals activates the yaw motors which turn the nacelle. To avoid wear and tear on the on the cables, the yaw movement is restricted. The WT have controls for regulating the performance by angling the blades according to wind speed. This is called pitch control system. If the blade angle is aerodynamically positioned, the WT performance is more effective. [11, p. 1-5]

2.1.2 Substructure

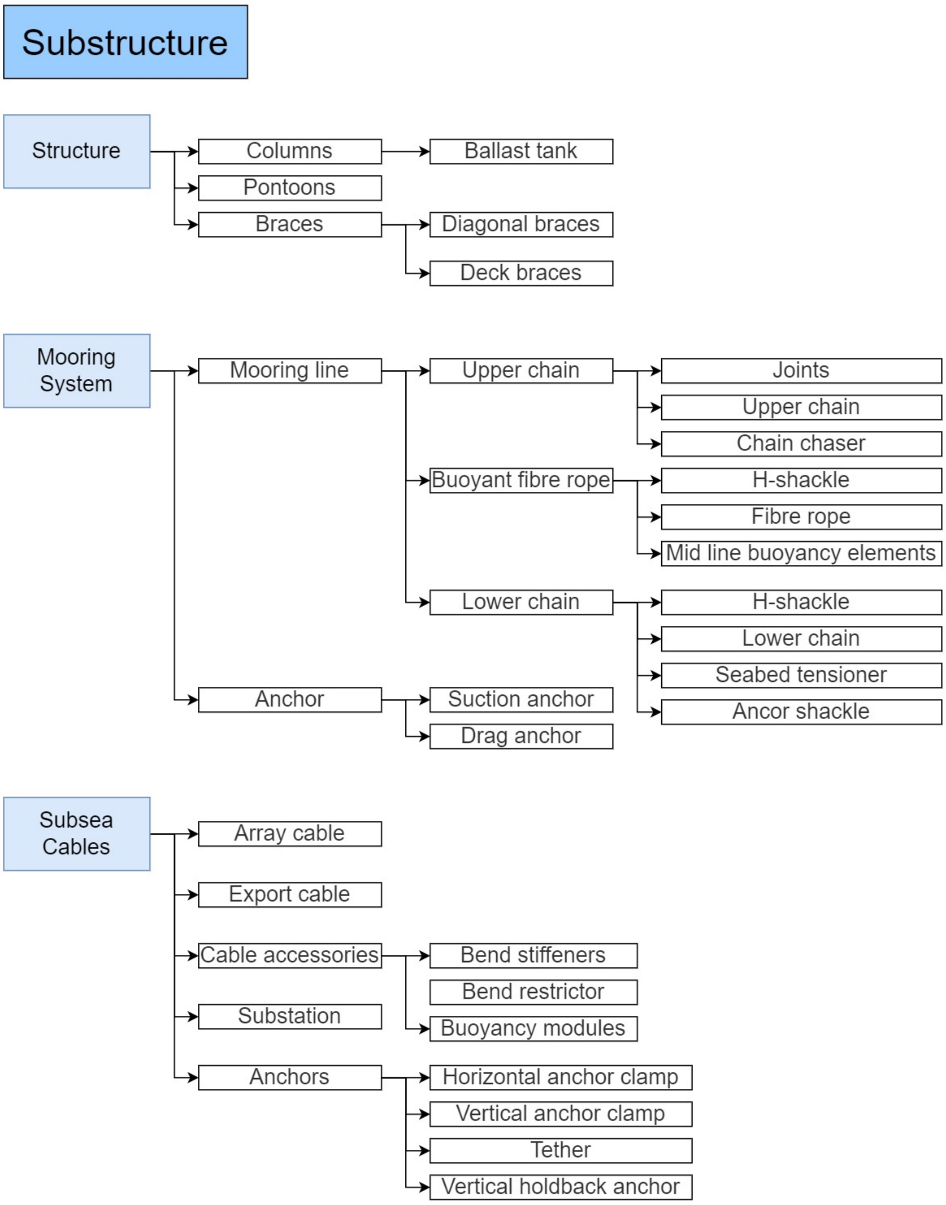

Figure 6: Technical hierarchy for the substructure of an offshore wind turbine

The substructure of an offshore WT varies a lot depending on water depths and conditions in the surrounding area. This thesis will look into greater water depths than 60 meters. Therefor floating support structure will be the focus, as shown in figure 7. The type of floating support structure OTL are planning to use is called semi-submersible substructures. [7, p. 78-82]

Other floating support structures are barge substructures, spar substructures and tension leg platforms [12].

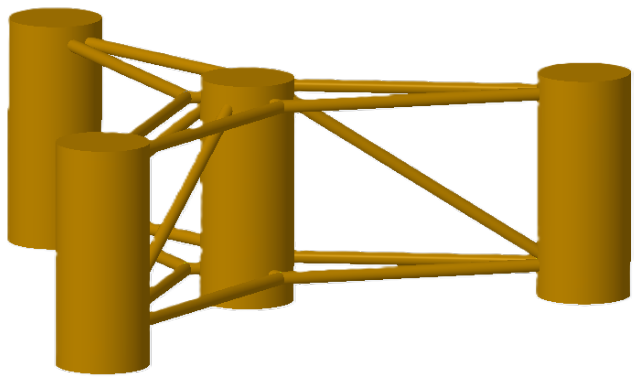

Figure 7: Simplified version of the offshore wind turbine; substructure. Modelled based on image of the Deepsea Star[13]

The structure consists of four buoyant columns forming a triangle with a column in the middle, shown in figure 7. An example of the dimensions of the substructure is shown in appendix A. Between each column there are deck braces and diagonal braces. On the bottom, connecting the columns, there are pontoons.[13] Pontoons are hollow and airtight, which helps with the buoyancy[12]. The columns are made of steel and are made to handle harsh environments. Inside there are ballast tanks to stabilize the floating offshore wind unit (FOWU). [13]

The FOWU has a complex mooring system to ensure right placement and safety. Odfjell's floating offshore wind unit (FOWU) are currently planning to have six mooring lines each[14]. An example solution is that each of the outer columns has two mooring lines, with one drag anchor and one suction anchor. This can vary according to needs. The mooring lines can be divided into three sections: upper chain segment, buoyant fibre rope segment and lower chain segment. [13]

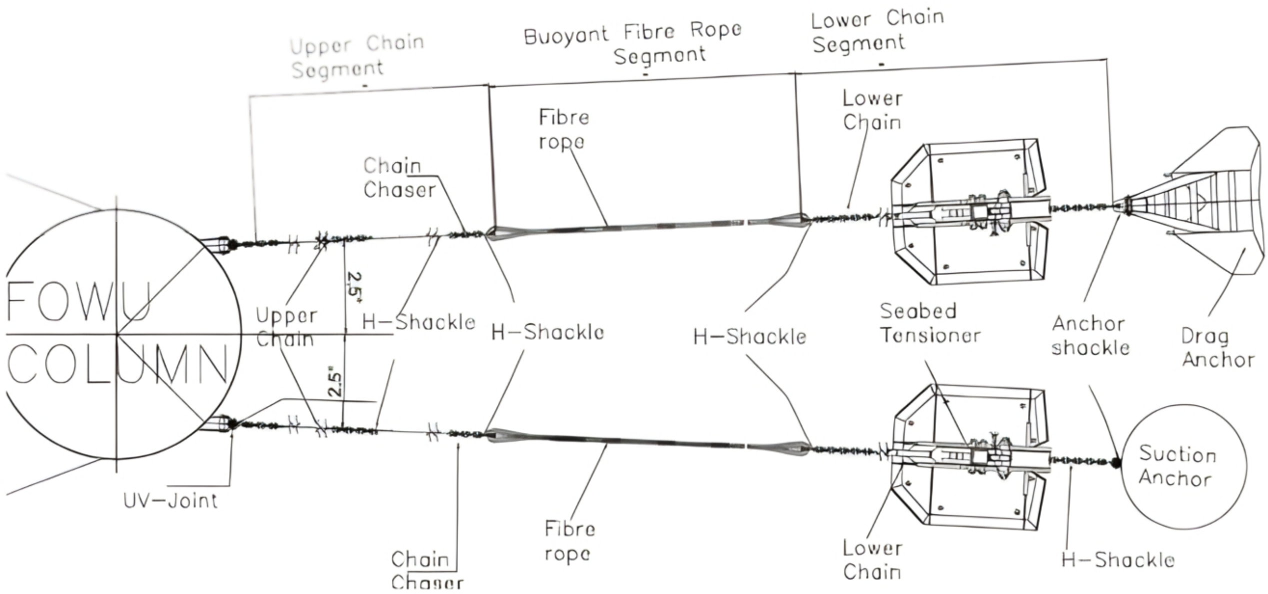

Figure 8: A generic sketch for mooring lines [13]

The upper chain segment is connected to the column with a joint. The joint is then connected to the upper chain, which has a chain chaser on the end. [13, p. 9] The chain chaser makes it possible to disconnect the FOWU from the anchors, which can be necessary for major maintenance operations where the FOWU needs to be transported to land[15].

The buoyant fibre rope segment consists of a fibre rope, H-shackles, and mid-line buoyancy elements. The fibre rope is connected to the chain chaser, from the upper chain segment, with a H-shackle. [13, p. 9] This segment often contains mid-line buoyancy elements, which will lift the fibre rope and therefore lift the lower part of the mooring line from the seabed[15].

The lower chain segment is connected to the fibre rope with a H-shackle. The lower chain segment starts with a chain, followed by a seabed tensioner. The tensioner is connected to the chain with a H-shackle and placed near the anchor. [13, p. 9] It is used to adjust the tension in the mooring lines [15]. The seabed tensioner is connected to another chain that is connected to the anchor with an anchor shackle. There are two types of anchors on the FOWU. One of the mooring lines have a drag anchor, and the other has a suction anchor. [13, p. 9]

A suction anchor holds suction, which requires a firm seabed. The anchor is embedded with its own weight into the seabed, and then suctioned to the firm ground. If the ground is to firm the anchor will not embed into the seabed and loose its function. The suction anchor can handle both horizontal and vertical loads. [16]

A drag anchor is embedded to the seabed by dragging the anchor trough the seabed with tension. For a drag anchor to work it needs cohesive sediments that the anchor can dig into. The drag anchor can only handle horizontal loads. [16]

The FOWU uses subsea cables to deliver power. A standard subsea cable consists of a stranded, profiled conductor surrounded by sealing layers, insulation, fillers, and protective armouring. [17]

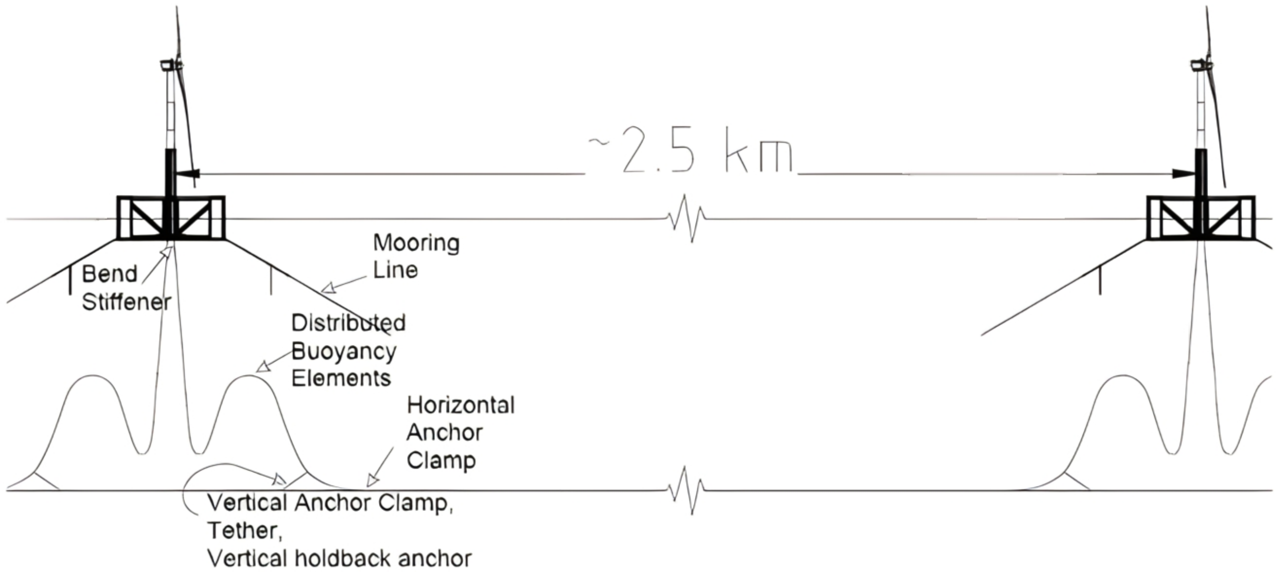

Figure 9: Generic sketch of cables and moorings [13]

The array cable transfers power from the WT to the substation. Additionally, the cable delivers fibre communication and power from the substation to the WT. Power is only delivered from the substation when the WT is not generating power.[18] The array cable has bend stiffeners which are located where the cable connects to the WT structure to prevent excessive bending[13, p. 9],[19]. To ensure less bending the cable uses buoyancy modules [13, p. 9]. The buoyancy makes the cable lay in a certain formation, often resembling waves[20]. This prevents cable fatigue caused by movement of the FOWU.

To anchor the remaining portion of the array cable to the seabed a horizontal and vertical anchor clamp, tether, and a vertical holdback anchor are used [13, p. 9]. Where the array cable transitions from a dynamic to a fixed cable on the seabed, a bend restrictor is installed. The bend restrictor forces the cable to follow a constant bend, and therefore avoiding overbending. [19]

The offshore substation links the array cables to the export cables. The substation has a transformer and equipment to manage power efficiently. For longer export cables, the substation might change the power from alternating current (AC) to direct current (DC) to reduce energy loss in the cables. Additionally, switches are located on the substation to protect the grid from disruptions from the wind farm, and conversely, to protect the wind farm from grid-related disturbances. [21]

2.2 GoliatVIND and Deepsea Star

OOW are planning to make an offshore wind farm in the Barents Sea called GoliatVIND. This project will be in collaboration with Source Galileo Norge and Kansai Electric Power. GoliatVIND will be located 85 kilometres northwest of Hammerfest. The wind farm will have five WTs, each with a capacity of 15 MW. GoliatVIND's purpose is to supply the offshore platform Goliat with renewable energy. Today Goliat is supplied with power from land with a 75 MW power cable. [14]

Figure 10: Picture of Odfjell Oceanwinds Deepsea Star [13]

OOW's Deepsea Star will be the floating structure. This is a semi-submersible substructure made from steel. Deepsea Star is designed in a triangle with buoyancy columns. To stabilize the FOWU the turbine is in the centre of the structure. Each side is approximately 100 meters long. The tower is placed on top of the substructure and is about 135 to 170 meters high, and the rotor have a diameter of 220 to 260 meters. This could make the WT approximately 300 meters high. [14]

Each FOWU have six anchors with an anchor line, and the anchors will either be suction or drag anchors. The anchors and size are decided by location specific analyses. The anchor line has a horizontal length of 1700 meters. An array cable is planned from each unit to a shared substation, and an export cable is planned from the substation to the Goliat platform. [14]

2.3 Maintenance

Maintenance is crucial for preserving the functionality and reliability of assets. By applying the proper maintenance methods, it will ensure optimal performance over time. This chapter will outline the framework of maintenance management as well as explore the different types of maintenance strategies.

2.3.1 Maintenance management

Maintenance management include all management activities related to setting the maintenance objectives, strategies, and responsibilities. This includes planning maintenance tasks, controlling their execution, and constantly seeking ways to enhance both the efficiency and cost-effectiveness of maintenance operations. [6, p. 5]

Maintenance management includes defining maintenance objectives, determine a maintenance strategy and implementing maintenance plans. The maintenance objectives can include targets centered around availability, safety, cost reduction, product quality, and so on. The management method applied to reach the maintenance objectives is called a maintenance strategy, which may involve outsourcing of maintenance, allocation of resource allocation, and more. A maintenance plan, on the other hand, is a more structured framework. This consist of a structured and documented set of tasks necessary to execute maintenance activities. [6, p. 5]

By effectively setting objectives, determining strategies, and implementing plans, maintenance management aims to ensure that assets are maintained in optimal condition, downtime is minimized, and organizational goals are achieved efficiently.

2.3.2 Different Types of Maintenance

There are two main categories in maintenance: Preventive and corrective maintenance.

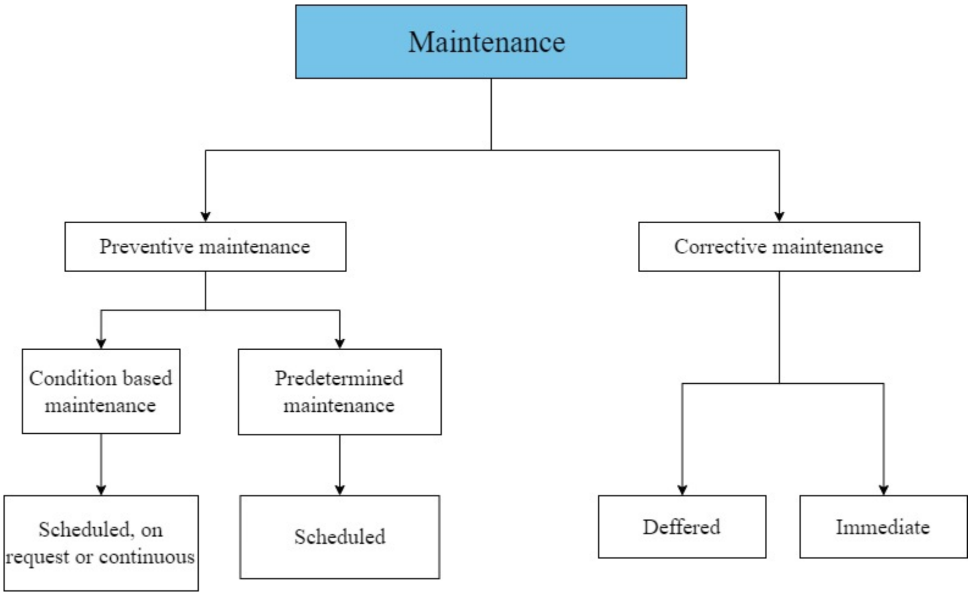

Figure 11: Overview of maintenance. Based on [6, Annex A]

Figure 11 shows the different sub categories in preventive and corrective maintenance. Corrective maintenance is when maintenance is carried out after a failure is detected. This can be done in two ways; Deferred, and immediate. Deferred corrective maintenance is referred to when the maintenance is not immediately done after fault detection. Still, it needs to be delayed inn accordance to given guidelines. Immediate corrective maintenance is carried out without delay after a fault detection. This is done to avoid unacceptable consequences. [6, p. 13]

Preventive maintenance is performed at scheduled intervals or based on specific criteria, aiming to minimize the likelihood of failure. The primary goal is to reduce downtime, but it could also be to minimize the consequence of failure. [22] Preventive maintenance can be divided into predetermined and condition based maintenance.[6, p. 12]

Predetermined maintenance is when the maintenance is executed at established intervals or numbers of use, which can be established from the failure mechanism of the item.[6, p. 12]

Condition based maintenance is a type of preventive maintenance that involves a combination of condition monitoring, inspection and testing to determine the need for maintenance actions. These actions can either be scheduled, on request or continuous. [6, p. 12]

Condition monitoring is defined as the activity, performed either manually or automatically, aimed at measuring the characteristics and parameters of an item's actual state at predetermined intervals [6, p. 14]. This monitoring is typically conducted while the equipment is in operation and can be continuous, at set time intervals, or after a specified number of operations. Unlike inspections, condition monitoring focuses on evaluating changes in parameters over time.[6, p. 14]
Predictive maintenance uses data from the asset to analyse and make predictions of future failures. Predictive maintenance is a type of condition based maintenance and is carried out based on predictions derived from analysis and evaluation of the significant degradation parameters of an item. [6, p. 12]

2.3.3 Condition based maintenance

Condition based maintenance (CBM) relies on real-time monitoring and analysis of the equipment condition to predict when maintenance should be executed. The aim of CBM is to detect early signs of deterioration and impending failure. In the standard DNV 0300 CBM is defined as ”preventive maintenance which include a combination of condition monitoring and/or inspection and/or testing, analysis and then ensuring maintenance actions” [23, p. 24].

2.3.4 Reliability centered maintenance

According to M. Rausands book System Reliability theory RCM is a ”systematic consideration of system functions, the way functions can fail, and a priority-based consideration of safety and economics that identifies applicable and effective PM tasks” [4, p. 401]. According to M. Rausand RCM is executed by answering these seven questions:

1. What are the functions and associated performance standards of the equipment in its present operating context?
2. In what ways can it fail to fulfil its functions?
3. What is the cause of each functional failure?
4. What happens when each failure occurs?
5. In what way does each failure matter?
6. What can be done to prevent each failure?
7. What should be done if a suitable preventive task cannot be found?

[4, p. 402]

The main goal of a RCM is to reduce maintenance cost. According to M. Rausand "a RCM analysis will focus on the most important functions of the system, and avoid or scale down maintenance actions that are not strictly necessary" [4, p. 401]. The function failure analysis (FFA) decides if the system needs a RCM analysis. The failure criticality needs to be measured by the four consequence classes:

- **S:** Safety of personnel
- **E:** Environmental impact
- **A:** Production availability
- **M:** Material loss

[4, p. 406]

If at least one of the classes are ranked as medium or high the function failure should be subjected for a RCM [4, p. 405-406].

The main steps for the RCM analysis are:

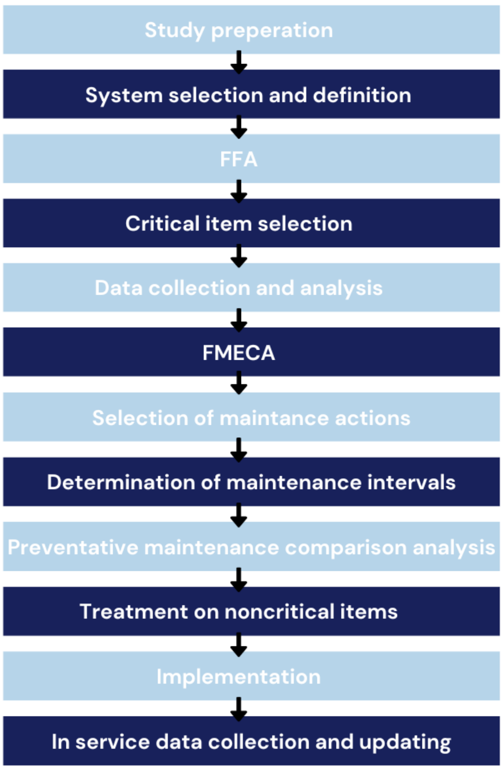

Figure 12: Main steps in a RCM analysis. Based on [4, p. 403]

2.3.5 Technical hierarchy

The technical hierarchy is crucial when creating a maintenance strategy. It provides an overview of equipment units, by giving each physical item an unique identifier, a tag. From ISO 14224 a tag number is defined as a ”unique code that identifies the equipment function and its physical location” [24, p.17]. The technical hierarchy gives an overview of connected equipment. It shows the relation between equipment. It should be developed at an early phase to have an overview of how the equipment is related. [25, p. 20]

2.3.6 Criticality

Criticality, in maintenance, is the degree of importance of an asset within a system [26]. Regarding maintenance management it is crucial to know the importance of different assets in a production process. Levels of criticality helps allocate resources effectively and prioritize critical components for the production. A determination of criticality is, in other words, a risk assessment. This will help to determine the maintenance strategy, like preventative or predicative strategies.

2.4 Monitoring

To determine which equipment requires maintenance, it is essential to understand the equipment's health. Therefore, monitoring of the equipment is crucial. This chapter will outline various techniques for monitoring equipment.

2.4.1 Supervisory control and data acquisition

Supervisory control and data acquisition (SCADA) is a system that collects data from different parts of the facility and sample date to help monitor and control the processes. This makes it possible to get all the information in real time, without having access to the WT. This information shall be evaluated in accordance with performance. When evaluating the performance, it is possible to discover future potential failures. [27]

The system consists of three main system components. It consists of either programmable logical controllers (PLCs) or remote terminal units (RTUs) that work as microcomputers. The microcomputers interact with the field devices (sensors etc). The data is transmitted from the equipment that requires monitoring, in this case WT components, to the human machine interfaces (HMIs), where the data is analysed. The HMIs can, in turn, transmit both manual and automatic control inputs to the PCLs or

RTUs, and subsequently issue commands to the control relays. [27]

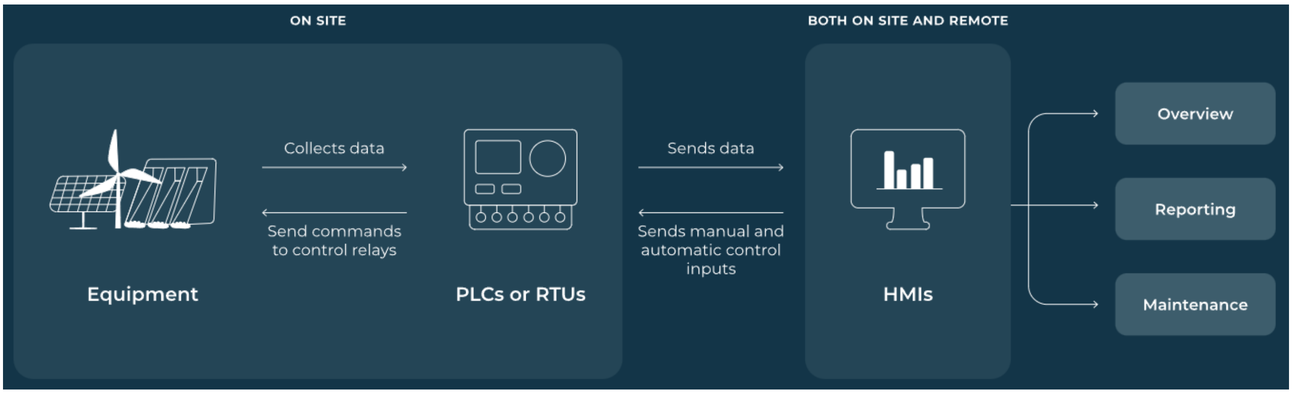

Figure 13: Illustration of how the components work together in SCADA [27]

2.4.2 Condition monitoring system

The condition monitoring system (CMS) is aimed at detecting changes as early as possible to predict developing faults. It predicts the health of equipment by using sensors for measuring parameters such as vibrations and oil debris and putting the data from the sensors in a monitoring software. This is done to minimize performance degradation and economic cost. One of the most important goals for the CMS is to make predicative maintenance possible. [28, p. 117-118]

2.5 Evaluation

To determine the effectiveness of the asset and maintenance tasks, it is essential to evaluate the performance regularly. Therefore, conducting thorough evaluations is crucial. This chapter will outline various techniques for evaluating the outcomes.

2.5.1 Spare part evaluation

Delivery time, cost, downtime, lost production costs, failure and repair data is necessary to perform a spare part analysis. A spare part analysis calculates the necessary number of spare parts needed; this includes data to ensure parts for unplanned failure. The analysis is done to prevent having unnecessary spare parts in storage. The availability of spare parts reduces downtime in case of failures, resulting in lower production costs. [29]

When doing a spare part evaluation it should follow the flow shown in figure 14:

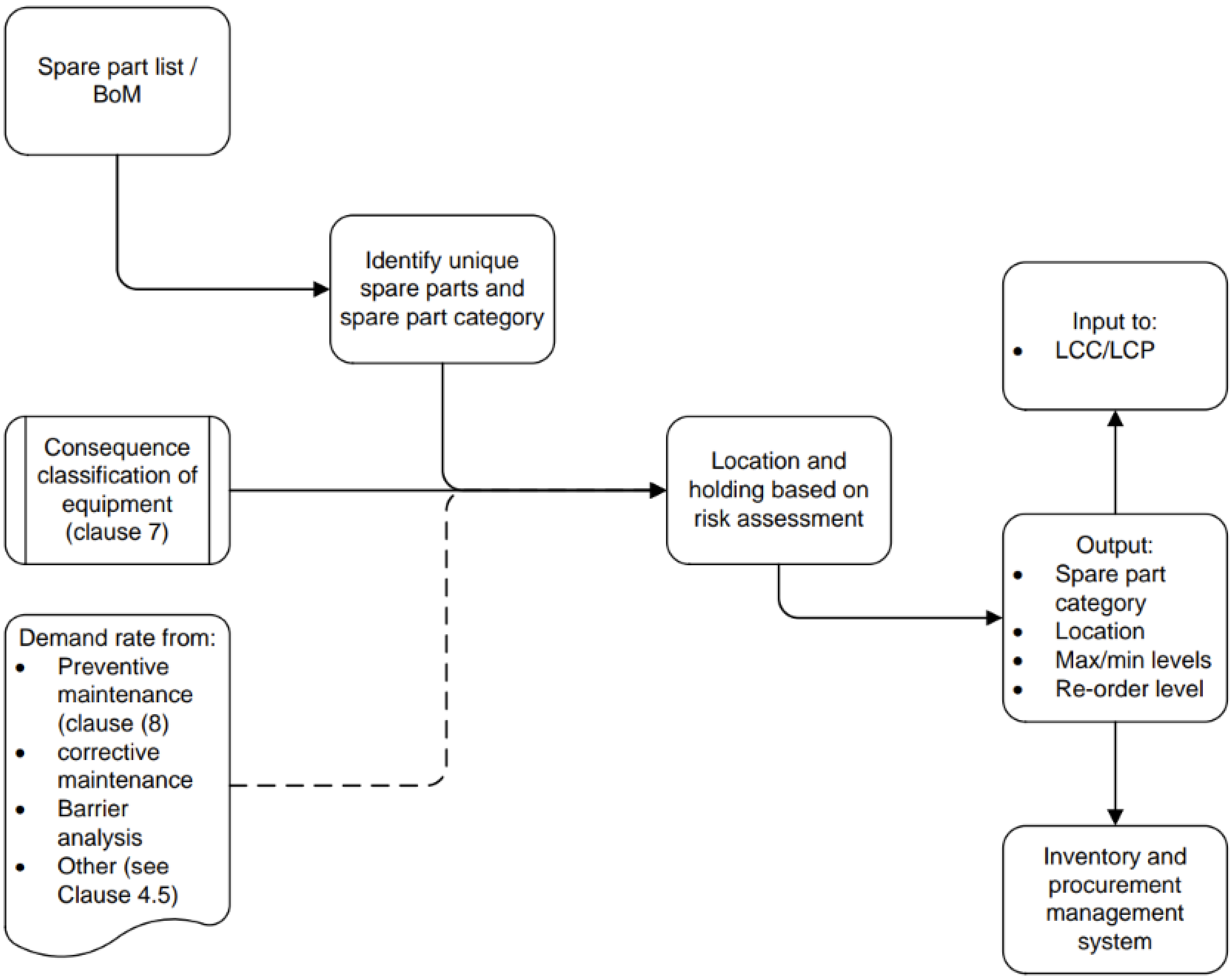

Figure 14: Evaluation of spare parts [25, p. 36]

Capital spare parts are parts that are "vital to the WT, but is unlikely to suffer a failure during the WT life cycle" [25, p. 36]. These spare parts have a long lead time and are often expensive. This is often ordered in the same package as the WT. To choose which capital spare parts are necessary, a risk assessment should be done before buying the initial system package. [25, p. 36-37]

Operational spare parts are "spare parts required to maintain the operational and safety capabilities of the equipment during its normal operational lifetime"[25, p. 36]. The operational parts are not frequently used.

Consumable spare parts are "items or materials that is not item specific and intended for use only once"[25, p. 36], for example: bolts, nuts and gaskets. These are often called first line spare parts and are frequently used.

When planning spare parts, it is necessary to consider failures in a time interval. After years of maintenance the mean numbers of repairs over the time interval t, W(t), can be calculated through:

$$W(t) = \frac{t}{MTTF + MDT} \quad [4, p.371] \tag{1}$$

W(t) will help find the demand rate of spare parts.[4, p. 371]

This equation shows that the mean number of repairs are dependent on the MTTF and MDT. MTTF is mean lifetime of the spare part and MDT is the downtime divided by the number of failures. By setting the input (t) to the operational lifespan of the asset, it is possible to find the number of spare parts that are needed for the time interval.

To evaluate spare parts for the WT the following risk matrix from NORSOK Z-008 is used.

Consequence / Demand rate	Low	Medium	High
First line spare parts, frequently used.	Minimum stock at site	Minimum stock at site and any additional spare parts at central warehouse	Adequate stock at site
Not frequently used.	No stock	Central warehouse, no stock at site	Central warehouse and minimum stock at site if convenient
Capital spare parts. Seldom or never used.	No stock	No stock	Holding optimized by use of risk assessment case by case

Figure 15: Risk matrix for spare parts [25, p. 45]

2.5.2 Root cause analysis

According to Tableau [30] root cause analysis is the ”process of discovering the root causes of problems in order to identify appropriate solutions” [30]. This method can show where systems failed or where the issue occurred in the first place. The core principles in a root cause analysis are listed below:

- Focus on correcting and remedying root cause rather than just symptoms
- Don‘t ignore the importance of treating symptoms for short term relief
- Realize there can and often are, multiple root causes

- Focus on how and why something happened, not who was responsible
- Be methodical and find concrete cause-effect evidence to back up root cause claims
- Provide enough information to inform a corrective course of action
- Consider how a root cause can be prevented in the future

[30]

There are several ways to perform a root cause analysis. One of the approaches is the ”5 Whys”. This method is performed by asking a deeper why-question to every answer, which can lead us to most root causes. It is suggested that 5 questions often lead to the root cause, but it can be more and less too. Another alternative is Change analysis/Event analysis. [30]

This can be done in these steps:

1. List all potential causes leading up to an event
2. Categorize each change/event by influence the organization have
3. Go event by event and decide whether or not it was related, correlated, contributing factor or the root cause.
4. Look at how to replicate or remedy the root cause

[30] A different method is the cause-and-effect fishbone diagram. This method is a more visual version of the 5 Whys. One start with the problem in the middle of the diagram, and then brainstorm the potential causes into categories. After grouping the categories, they are split into smaller parts, and causes and sub-causes are looked thoroughly into. An example of a fishbone diagram is shown below. [30]

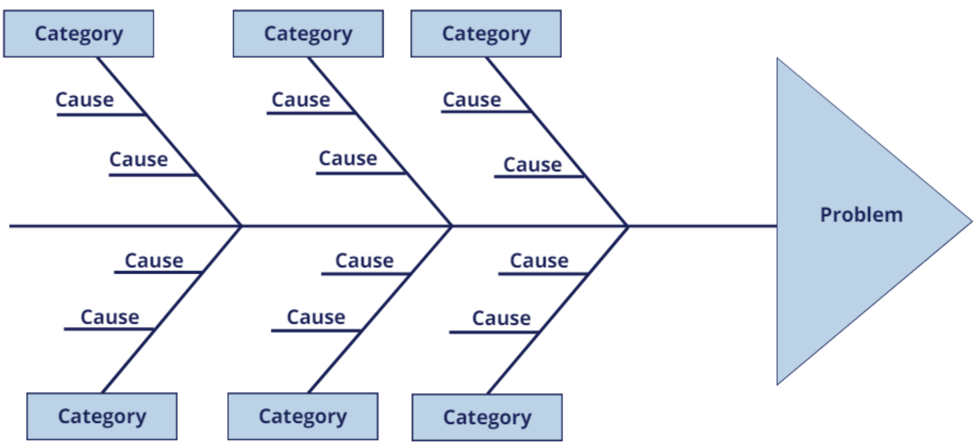

Figure 16: Example of a fishbone-diagram. Based on [30]

2.5.3 Gap-analysis

A gap analysis compares the current performance with the desired performance. There are several types of gap analyses. A strategic gap analysis is an internal review of how the company is performing against the long-term benchmarks, and goals. A skill gap analysis looks at the personnel element of the organization. It discovers if there are lacks in competence and training. It can be performed in the steps below. [31]

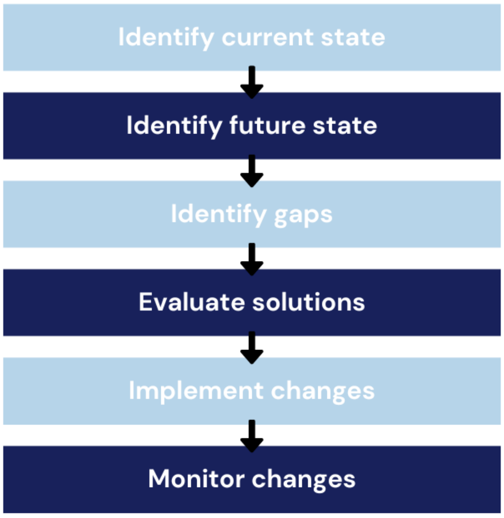

Figure 17: Steps in a gap analysis. Based on [31]

3 Summary of ISO 55000

3.1 Asset life cycle

An asset is any resource owned by an individual or organization that has economic value and can be utilized to generate future benefits. Asset life cycle is the stages an asset goes through from its creation to its disposal. There are typically five stages: plan, acquire, use, maintain and disposal. [32]

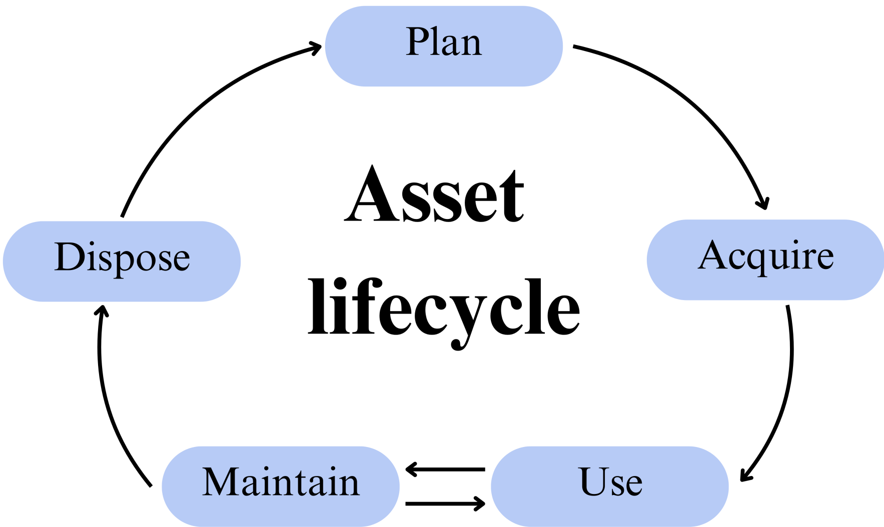

Figure 18: Asset life cycle. Based on [32]

The goals of managing an asset life cycle is to extend the functional lifetime of an asset and maximizing the value and utility of the asset throughout its entire lifespan. By properly utilizing and maintaining the asset, organizations can maximize its efficiency, minimize downtime, and ultimately achieve greater returns on their investment. [32]

3.2 ISO 55000

ISO 55000 defines asset management as ”coordinated activity of an organization to realize value from assets” [5, p. 14]. An asset can be explained as an item that has value. The value can both be intangible or tangible. [5, p. 2]
Asset management is about finding the right balance between costs, opportunities, and risks to meet the organization’s objectives. [5, p. 3]

AM is based on alignment, leadership and assurance. An asset management system (AMS) helps to direct, coordinate and control asset management activities. The function of the AMS is to set the AM policy, the objectives, and what processes are required to reach the objectives. The AM plan helps connect the AMS to technical AM requirements. Figure19 shows the relation between the AMS and AM. [5, p. 4-5]

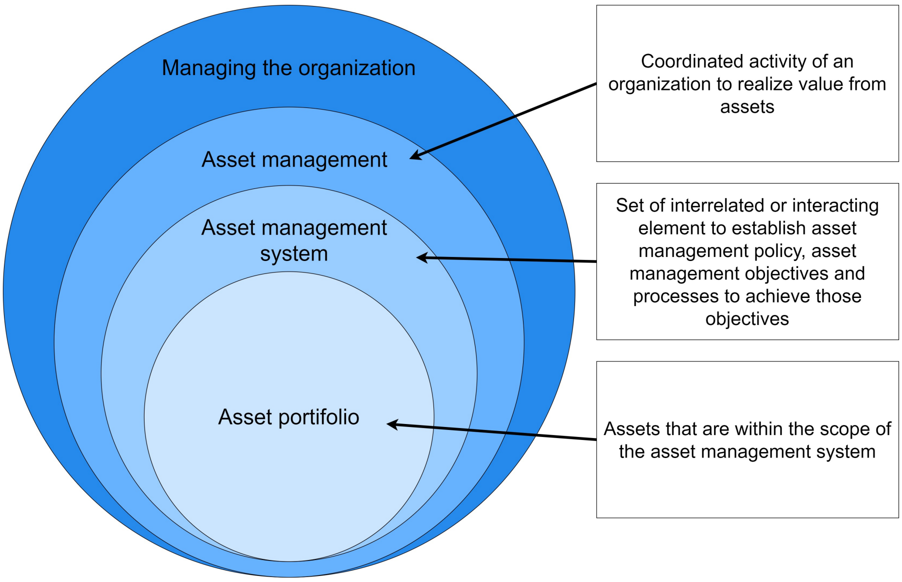

Figure 19: Relationship between key terms. Based on [5]

Implementing AM have several advantages. A few of the benefits can be improving the return on investments, reducing financial losses, improving health and safety. AM can also minimize environmental and social impact, assuring performance of assets, improved organizational sustainability, efficiency, and effectiveness. [5, p. 2]

3.3 ISO 55001 and ISO 55002

The ISO 55001 standard does not dictate what to do to manage physical assets, it provides requirements for how to operate the system. This provides a great deal of flexibility in what the user does. ISO 55002 shows how to apply the requirements in ISO 55001 to an asset management system. [33, p. 1] ISO 55001 and 55002 contains seven areas of compliance:

- Context of the organization
- Leadership
- Planning
- Support
- Operation

- Performance evaluation
- Improvement

[34, p. 3]

Figure 20 illustrates how the various components of the asset management process are integrated.

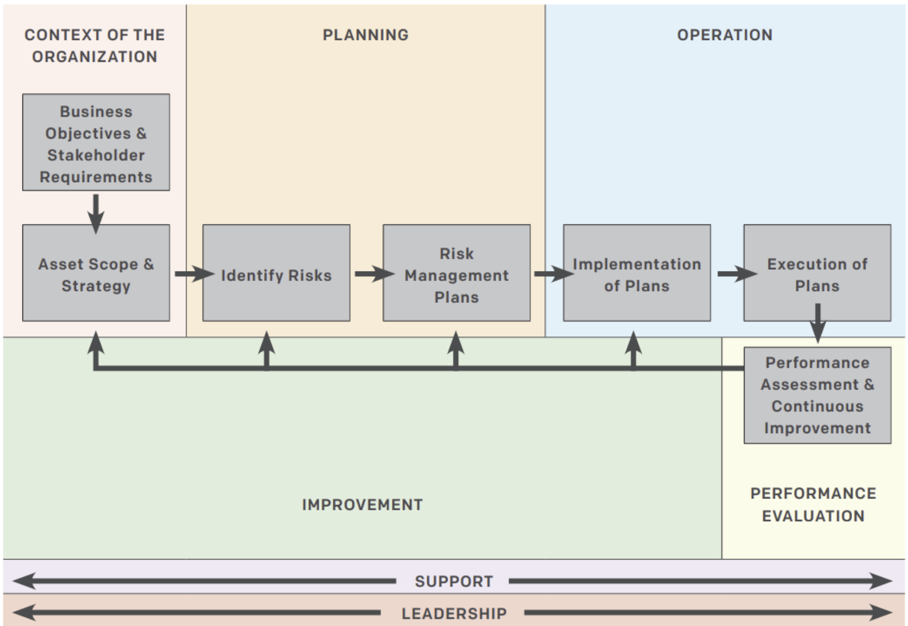

Figure 20: Typical comprehensive asset management process depicting ISO 55001 elements [34]

3.3.1 Context of The Organization

ISO55001 states that it is important to get an understanding of the organization and its context. The organization is responsible for identifying external and internal factors that affect how well your asset management system (AMS) will meet its outcomes. To understand the organization, it is important to understand the need and expectations of stakeholders, and to determine the scope of the AMS. [35, p. 1-2]

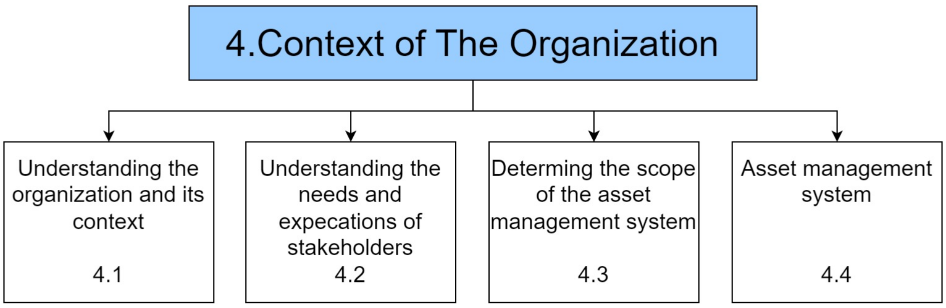

Figure 21: Subsections within the 'Context of the organization chapter. Based on [35, p. 1-2]

When an AMS is being established or reviewed it should be consistent and aligned with the context of the organization. One must take account for the internal context such as risk management plans, policies, objectives, and strategies, but also the external context like the social, cultural and political environment. [33, p. 1-6]

3.3.2 Leadership

ISO 55001 states that top management is responsible for developing and aligning the asset management policies and objectives with the organizational objectives. Leaders at all levels should be involved in the planning, implementation, and operation of the AMS. The top management and leaders at all levels should ensure that appropriate resources are in place to support the AMS. Potential conflicts between the internal culture of the organization and its AMS should be resolved by leaders. [35, p. 2-3]

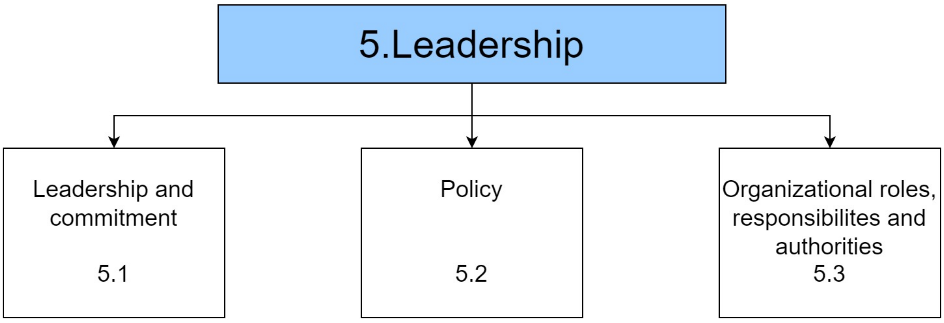

Figure 22: Subsections within the 'Leadership' chapter. Based on [35, p. 2-3]

ISO 55002 goes in depth on how top management can demonstrate their commitment to AM. This can be done by i.e. making references to AM principles in communications or monitoring the AMS performance and ensuring corrective or preventive actions. It also explains what commitments a company policy should include, and what considerations should be given when assigning internal roles. [33, p. 6-7]

3.3.3 Planning

According to ISO 55001 the organization "shall plan actions to address risks and opportunities" [35, p. 4]. When the organization has addressed risks and opportunities, the organization will be able to reach its objectives, prevent or reduce undesired effects and have continual improvement. [35, p. 3]

Asset management objectives are goals to be meet in the AM. These objectives should be based on requirements from stakeholders, and other requirements such as financial, legal, and organizational requirements. [35, p. 4-5] To meet the objectives planning is required. ”This includes but is not limited to: method and criteria for decision making, prioritizing activities and resources, responsibility, completion, actions to address risks and opportunities and evaluation”[35, p. 4].

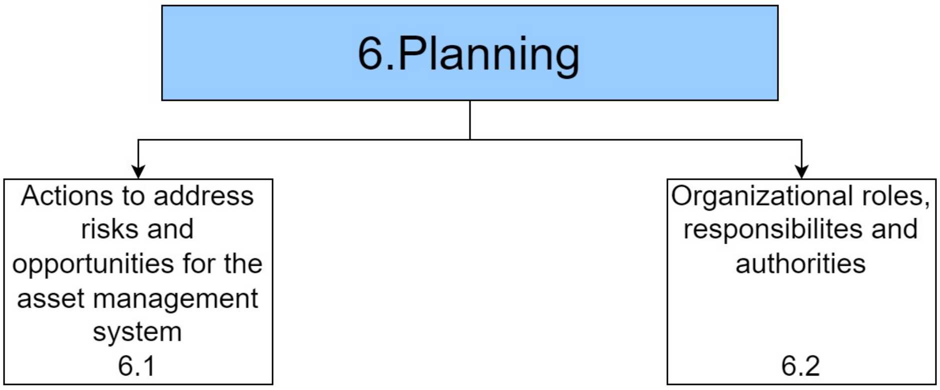

Figure 23: Subsections within the ’Planning’ chapter. Based on [35, p. 3-5]

ISO 55002 goes more in depth on how the organization should determine necessary actions for addressing risk, when planning its AMS. It states that when setting AM objectives, risk should be considered. Planning should also involve evaluating how important assets are for achieving their goals and making sure these objectives match up with what the organizations goals and requirements. Additionally, various issues related to asset portfolio, asset systems, and individual assets are addressed through the objectives for asset management. [33, p. 8-14]

3.3.4 Support

For an organization to have effective management it is important that the support is easily accessible and controlled. The organization should map all available resources according to its planned activities. That way the gaps are easily found through a gap analysis. The gap analysis can help with determining options when resourcing the activities. There should also be a plan for prioritizing the activities, so that the resources are utilized efficiently. [35, p. 5-7]

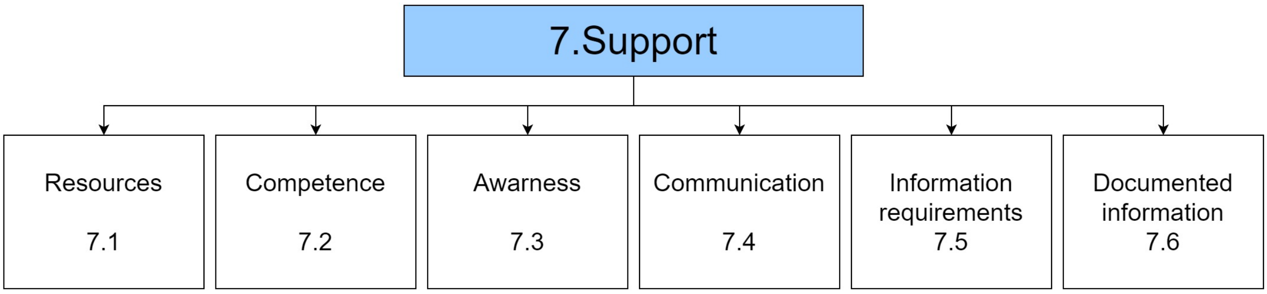

Figure 24: Subsections within the 'Support' chapter. Based on [35, p. 5-7]

ISO 55002 covers how the organization should map its resources to identify gaps. It lists what the resulting competency improvement and training plans could include and how the AM activities carried out should be communicated to relevant stakeholders. The standard also gives an explanation on what should be considered when creating a communication plan and what it should include. [33, p. 14-16]

3.3.5 Operation

Operation involves the execution of asset management plans. This includes documenting evidence of execution and ensuring the organization regularly looks at and deals with ongoing risks. Additionally, the operation part defines the requirements of the parts of the project that is outsourced. It is crucial to verify that these outsourced parts comply with the organization's requirements. [34, p. 3]

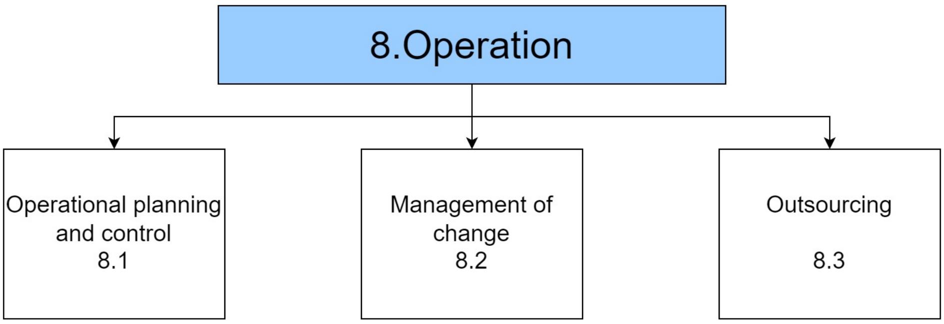

Figure 25: Subsections within the 'Operation' chapter. Based on [35, p. 8]

ISO 55002 states that the organization should have an operational planning and control process. This should show who is responsible for the planning and how the activities will be executed. It should include who does what, what steps need to be taken, what resources are needed, and how they'll be distributed. Additionally, competency development should be considered. The control process should include a way to measure process and criteria for internal audits and schedules as well. [33, p. 18]

The processes and actions determined in the risk assessment should be implemented by "establishing criteria for risk management processes, controlling implementation of these processes based on the defined criteria, and keeping documentation that demonstrates that the risk management processes have been executed as planned" [35, p. 8]. Emerging risks and their impact should be considered, and the organization should be able to plan changes with sufficient time to act if necessary. Both planned and unplanned changes affecting assets should be evaluated and actions necessary should be taken before implementation of the changes. All risks associated with the changes should be evaluated. [33, p. 19-20]

The organization can outsource activities. Outsourcing involves delegating activities to an external or internal service provider. When outsourcing the organization needs to formalize the relationship with a contract or an agreement. The organization still needs to control the actions to ensure that performances is as planned. [33, p. 20]

3.3.6 Performance evaluation

This part defines how evaluation of performance shall be executed. This includes requirements for the on-going monitoring, auditing, and evaluation of asset performance. Additionally, it includes requirements for the asset management system itself. It is important to include descriptions of what, when and how performance is evaluated. [34, p. 3]

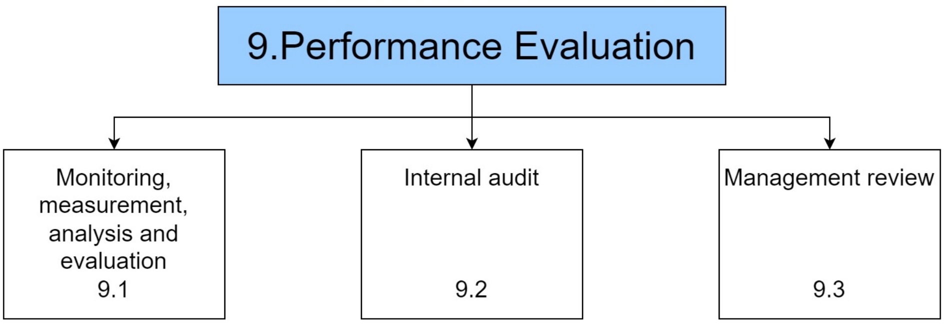

Figure 26: Subsections within the 'Performance evaluation' chapter. Based on [35, p. 8-10]

An evaluation should verify whether the procedures are effective and up-to-date, and if the AM plan and processes are effectively communicated to stakeholders. Internal audits should be conducted to ensure the AMS conforms to its requirements. The management should review the assets, AMS, AM activity, the operation of the policy, objectives, and plans at planned intervals. The inputs for the review should include changes in external and internal issues, nonconformities, corrective actions, monitoring, and measurement results. The results from the management reviews should cover the decisions and actions for improvement in the AMS. It should also include criteria for decision making, variations of the scope, policy and objectives. [33, p. 21-26]

3.3.7 Improvement

Improvements are the last thing to be carried out. To improve the AMS, the nonconformities needs to be documented and evaluated. Actions need to be done to prevent nonconformities, such as appropriate documentation, correct implementation, and management. Corrective and preventative actions needs to be implemented in the AMS to secure continual improvement of the AM. [34, p. 4]

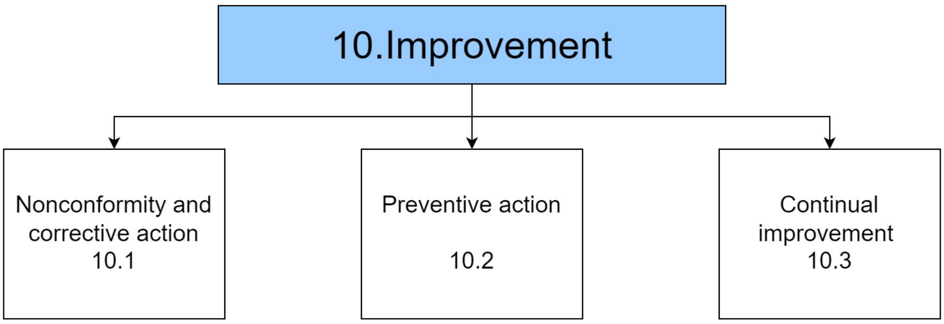

Figure 27: Subsections within the 'Improvement' chapter. Based on [35, p. 10-11]

This should be done by reviewing previous nonconformities and how the nonconformities were dealt with. The organization should establish the processes needed for initiating corrective actions. The actions should be proportional with the risk associated with the asset and integrated into the asset management system. The organization should establish and implement preventive processes to address failures before they occur. This should be done by using the right methodologies. The organization should seek knowledge about new technology regarding asset management, to ensure continual improvement of the AMS. [33, p. 26-28]

4 Methodology

4.1 Literature Review

A literature review is a critical and systematic examination of existing literature and research that are relevant to a specific topic or research question. This involves identifying and analysing sources such as books, journal articles and other publications. In this thesis different standards will be thoroughly analysed. The aim of a literature review is to establish an overview of existing research and discover what gaps that needs to be filled. This will establish a foundation for further research. When executing a literature review it is important to be critical of the publications and sources. [36]

4.2 Qualitative and quantitative method

"Research methods are the strategies, processes or techniques utilized in the collection of data or evidence for analysis in order to uncover new information or create better understanding of a topic" [37]. There are several ways to classify research methods, but one of the most common separations is between qualitative and quantitative research. Gathering information from interviews and texts are qualitative methods. Quantitative methods are based on statistics. The research design has consequences for the choice of research method. The thesis is written in the inductive perspective, which makes the qualitative method applicable. Techniques and tools used to gather data in the qualitative method are interviews, focus group interviews, observations, and document analysis. In qualitative research data is gathered about lived experiences, behaviours or emotions and the meanings individuals have attached to them. [37]

4.3 Interview

There are three types of interviews that is usually applied in qualitative research: structured, semi-structured and unstructured. Structured interviews are where a set of questions are asked in order, like a verbal survey. Unstructured interviews have a list of topics, and no predetermined questions. This makes the interview more flexible, but the reliability is decreased. The last category is semi-structured interviews, this requires a list of questions and topics to be pre-prepared, but the questions can be asked in different ways, which increases the flexibility of the interview, and increasing the credibility of the data. In this thesis semi-structured interviews will be performed to get the most credible data. [38]

5 Interview

Personnel from OOW and OTL were interviewed to help with the development of the maintenance strategy.

5.1 Hypothesis

There are currently no maintenance strategies for OOW's FOWU. The aim of the interview is to reveal what is necessary to develop a maintenance strategy for the FOWU. OTL has 50 years of experience in maintaining offshore oil rigs. There is an expectation that several of these procedures can be implemented on wind turbines.

Since the wind turbines are planned to be located offshore, there is an expectation that there will be logistic issues due to the distance. There will also be limited access and visual inspections. Because of this there is an expectation that preventative maintenance will be preferred, but with a different approach compared to the existing the oil rigs. The offshore environment is a harsh environment. This factor is expected to be taken into consideration in the planning phase. Challenges that can appear from the result of the interviews are different expectations, bad communication and problems with the cooperation between the companies and different suppliers.

5.2 Questions

For the maintenance strategy to cover the different elements of ISO55000, the standard was used in the development of the questions. Table 1 and table 2 list the question in the white row, and what part of the standard they cover in the light blue row.

5.2.1 Odfjell Oceanwind

Interview questions OOW
What departments and third parties are going to be involved in GoliatVIND?
4.2 Understanding the organization and its context, 7.4 Communication
How do you communicate across different departments and third parties?
7.4 Communication
What are your goals for maintenance of the wind turbines? (Downtime, PM)
4.3 Determining the scope of the AMS, 6.2 Asset management objectives and planning to achieve them
Do you have any specific plans/wishes for maintenance on Deepsea Star/GoliatVIND?
4.3 Determining the scope of the asset management system, 6.1 Actions to address risks and opportunities for the AMS, 6.2 Asset management objectives and planning to achieve them
How far have you come in the development of the Deepsea Star?
4.1 Understanding the organization and its context, 7.2 Competence
What challenges have you met so far?
6.1 Actions to address risks and opportunities for the AMS
Could OOW like to have the responsibility for maintenance and CMMS for the entire turbine?
4.2 Understanding the needs and expectations of stakeholders, 8.3 Outsourcing
How do you define critical parts?
5.2 Policy, 6.1 Actions to address risks and opportunities for the AMS, 7.5 Information requirements
Where do you wish to store spare parts?
6.1 Actions to address risks and opportunities for the AMS, 8.1 Operational planning and control

Table 1: Interview questions for OOW

5.2.2 Odfjell Technology

Interview questions OTL
How do you communicate across departments and third parties?
7.4 Communication, 8.1 Operational planning and control
How do you build maintenance? Is it important to have a maintenance program in place before a system is implemented/installed?
6.1 Actions to address risks and opportunities for the asset management system, 8.2 Management of change
What kind of analyses are done to create a maintenance program in the maintenance system?
6.1 Actions to address risks and opportunities for the asset management system, 7.1 Resources, 8.1 Operational planning and control, 9.1 Monitoring, measurement, analysis and evaluation, 10.2 Preventive action, 10.3 Continual improvement
What maintenance routines are you currently using? (any routines that can be implemented for turbines)
7.1 Resources, 7.2 Competence, 7.3 Awareness
What procedures do you have for risk evaluation? Do you have a risk matrix?
5.1 Leadership and commitment, 6.1 Actions to address risks and opportunities for the asset management system, 7.3 Awareness, 7.5 Documented information
Do you have any specific plans/wishes for maintenance?
6.2 Organizational roles, responsibilities and authorities, 9.1 Monitoring, measurement, analysis and evaluation
Do you have a standard for prioritizing maintenance of components?
5.2 Policy, 8.1 Operational planning and control
What big challenges do you think you will face in relation to maintenance on wind turbines?
6.1 Actions to address risks and opportunities for the asset management system, 7.1 Resources, 7.3 Awareness, 8.1 Operational planning and control
How are you planning on accommodating OOW with competence?
7.2 Competence
How can you deliver a full CMMS system to OOW?
8.1 Operational planning and control, 10.2 Preventive action, 10.3 Continual improvement
Do you have any specific data systems for maintenance?
7.4 Communication, 7.5 Information requirements, 8.1 Operational planning and control
What methods are used to process deviations and accidents?
10.1 Nonconformities and corrective action, 10.2 Preventive action, 10.3 Continual improvement
Where do you wish to store spare parts?
6.1 Actions to address risks and opportunities for the asset management system, 7.1 Resources, 8.1 Operational planning and control
Extra question: Do you think you will be able to predict when spare parts are needed, so that one can order directly from the supplier and not have to store it?
6.1 Actions to address risks and opportunities for the asset management system, 7.1 Resources, 8.1 Operational planning and control
How do you handle spare parts? (Storage, transportation, system)
6.1 Actions to address risks and opportunities for the asset management system, 7.1 Resources, 8.1 Operational planning and control

Table 2: Interview questions for OTL

5.3 Results from the interviews

The results are split into two subsections. The first one is interview with personnel from OOW, and the second one for the interview with OTL.

5.3.1 Odfjell Oceanwind

What departments or third parties are going to be involved in GoliatVIND?
Third parties involved will be wind turbine supplier, supplier of other equipment and systems. Demands from the suppliers are going to be input in the maintenance program for OOW.

How do you communicate across different departments and third parties?
In the current state, we use Aconex which is a documentation management system and project management system. Today we work with design and supply chain, but in future states additional program might be needed. When moving into detailed engineering phases, as we call it, with different suppliers/contractors an additional system might be required for collaboration with all parts involved. If this is the case, then data collected from this system shall be input to the Computerized maintenance management system (CMMS). No matter the system, what is important is that all design, engineering, fabrication, and commissioning data gets collected and transferred to the CMMS, including maintenance recommendations from suppliers. This data will further be used in the reliability centered maintenance (RCM) approach. In future states the program needs to gather data and information from the suppliers, which will be input to the operations and maintenance (O&M) system.

What are your goals for maintenance of the wind turbine? (PM, downtime)
The main targets from the O&M strategy are to ensure reliable power production and to preserve the 25 years of lifetime on the FOWU, and potential lifetime extension. Another target is to have the least amount of downtime, the target for wind turbine availability will be 97,5%.

Do you have any specific plans/wishes for maintenance on Deepsea Star/GoliatVIND?
We demand everything to be managed from land. We are using a RCM approach where all components are looked at, and the criticality of the components are determined. RCM also finds failures, consequences, how the failure affects other systems and cost. Maintenance and inspections are then based on the RCM. We want to find out what type of maintenance individual components needs.

How far have you come in the development of the Deepsea Star?

We are working on the basic design and the main parameters on the design are done. At the same time as we are working on the basic design, we are working on project specific design that will be used at GoliatVIND. This will contain requirements from the GoliatVIND project. The supplier of the WT also has impact on the design. We are also working on getting a supply chain established. There is a framework agreement in place with Siemens Gamesa, but it is not yet decided if this will be used for GoliatVIND. We are not sure if the WT's will be direct drive or gear driven, that will depend on the supplier.

What challenges have you met so far?
A supply chain is hard to establish because this is a new industry. As well, there are a lot of components that are specific for ocean wind i.e. sub-sea power cables. Additionally, there is a high demand from other industries.

We are designing the Deepsea Star for 15MW turbines, which are the largest turbines currently on the market. These large turbine dimensions introduce some challenges to the Deepsea Star design. The challenge with current projects only having smaller turbines (typically up to 8MW), could be that there is not much operational data available for 15MW turbines (failure rates, mean time to failure (MTTF), etc.). Overall, there is also a lack of information on how floating turbines will affect the operational performance of the turbines (as most projects with longer operational experience are bottom fixed).

Could OOW consider taking responsibility for maintenance and CMMS for the entire wind turbine? If so, what qualifications/expertise/knowledge would the company need?
This might be something for consideration for the future, but as it is now this is the wind turbine generator (WTG) suppliers' scope and responsibility.

How do you define critical parts?
The equipment that has impact on safety is the critical parts. Also, there are strategic components that are important to have in place to reduce downtime. There are also components that frequently fail, which need to be replaced at frequent intervals. It is critical to have the opportunity to obtain the larger and more expensive component that may fail. Everything is critical depending on how one defines it.

Where do you wish to store spare parts?
We wish to store spare parts as close to the WT farm as possible, to get the least amount of time to get it out there. We think that we can predict when the big components will fail, so that we can order

it, and have it delivered when they fail. Then, we don't have to store it. Big components typically include blades, generator, transformer, etc. (also known as major components). Upon failure of these components a substantial offshore operation or tow to shore is likely required, known as heavy maintenance or major component exchange. These are the events that we believe we can predict with sufficient time to mobilise spare parts and prepare for the operations. In the future if we get more projects (GoliatVIND, Utsira Nord) we will explore coordinating storage units. We want the storage units to be located onshore and keep the storage offshore to a minimum.

5.3.2 Odfjell Technology

How do you communicate across departments and third parties?
We use teams across departments and mail with third parties.

Extra question: do you have knowledge to Aconex?
No, we use Proarc. This is not for third parties but as an internal- joint document register.

How do you build maintenance? Is it important to have a maintenance program in place before a system is implemented/ installed?
We build maintenance based on original equipment manufacturer (OEM) recommendations, the customer's internal procedures, and the RCM approach. The maintenance program is the content of a maintenance system, so the answer is split in two. One should know how the system is setup before one creates the program, but elements from the program also need to go into the system.

What kind of analyses are done to create a maintenance program in the maintenance system?
To create the program, consequence classification, FMECA, RCM analysis and spare part evaluations are performed. For the maintenance plan, we are trying to have a running PM program split through the whole year to avoid spikes in PM.

What maintenance routines are you currently using? (any routines that can be implemented for turbines)
We use inspection routines, setting up first line maintenance and generic preventative maintenance (PM) from OEM demands. For wind turbines we have to look into the use of condition based maintenance (CBM) due to availability.

What procedures do you have for risk evaluation? Do you have a risk matrix?

We have a lot of different risk evaluations, but for maintenance a version of 5x5 L1 procedures is used. It has the same criteria but in a 3x3 matrix not 5x5.

Do you have any specific plans/wishes for maintenance?

The wish and the plan is that the customer assets and personnel shall be taken care of when it comes to health, environment and safety. The maintenance shall be good enough to ensure safe working conditions.

Do you have a standard for prioritizing maintenance of components?

The consequence analysis and FMECA are the criteria that sets the prioritizing of the maintenance, in addition to due dates for corrective maintenance.

What big challenges do you think you will face in relation to maintenance on wind turbines?

The biggest challenge will be to put together a system where CBM is the controlling factor for when maintenance is necessary. We want as little maintenance as possible on the turbines, therefore they need to be monitored well with CBM techniques.

How are you planning on accommodating OOW with competence?

We are planning on being able to offer OOW a maintenance program, maintenance system and engineering competence to ensure as much running time and lifetime for their wind turbines.

How can you deliver a full CMMS system to OOW?

Help them set up maintenance within IFS which is a enterprise resource planning (ERP) system with maintenance module, or by helping them set up Maximo , which is a EAM system based around the maintenance concept and logistics, finance, supply chain, management are support tools for optimal focus on maintenance.

Do you have any specific data systems for maintenance?

We have two CMMSs available; one is IFS which is an ERP system with maintenance module and the other is Maximo which is a maintenance system with extra functions. Maximo is a maintenance program while IFS are more of a company program with a maintenance module.

What methods are used to process deviations and accidents?

We use Synergi, which is a data system used internally and across Odfjell. It registers all unwanted events.

Where do you wish to store spare parts?

We cannot comment on where we wish spareparts are store, but we recommend using criticality levels for equipment to identify what would be critical spare parts, these should be stored as close as possible to the windpark for reduced downtime.

Extra question: Do you think you will be able to predict when spare parts are needed, so that one can order directly from the supplier and not have to store it?

It would be the most optimal, because you can order and deliver the parts in time for when you need it. That is ideal because storage costs are expensive. Where one can use the ”just in time” principle it is used, but with the current world picture it becomes more and more scary to use this methodology (Example: Suez Canal). This could lead to a potential vulnerable situation, where you get more downtime than what is wanted. Close consideration needs to be done when it comes to this.

How do you handle spare parts?(Storage,transportation,system)

We have lists of all equipment, and all the spare parts of the equipment are registered in CMMS.There we get an item number or part number, with all metadata connected to the equipment.

6 Results

6.1 Context of the organization

The organization shall define internal and external issues and how they affect the objectives. It is crucial for the organization to understand the needs and expectations of stakeholders. When all the external and internal issues and the need and expectations of stakeholders are gathered, the scope of the AMS is determined. [35, p.1-2]

6.1.1 Scope

This maintenance strategy explains the maintaining of the topside, substructure, cables, and mooring lines of Deepsea Star. It will use a combination of RCM and CBM methods. The strategy aims to maximize reliability, minimize downtime, and optimize maintenance activities to ensure the WT's optimal performance and operational life.

6.1.2 External and internal issues

ISO 55001 states that the organization shall ”determine relevant external and internal issues of the AMS”[35, p. 2]. This can be determined with a SWOT-analysis. The analysis consists of the internal strengths and weaknesses, and the external opportunities and threats [39].

6.1.3 Objectives

The objectives for the maintenance strategy gathered from the interviews are:

- Ensure reliable power production
- Preserve the 25 years of lifetime of the FOWU
- Minimize cost
- 97,5% availability
- Ensure safe working conditions

6.1.4 Requirements

According to ISO 55001 ”the organization shall determine the requirements and expectations of stakeholders with respect to the AM” [35, p. 1]. A general requirement for a maintenance strategy is to follow regulations. Det Norske Veritas (DNV) has several regulations for maintenance of offshore units, for example DNV-RU-OU-0512. OOW requires to control as much as possible remotely from a land base. To do this, monitoring needs to be autonomous, and maintenance needs to be thoroughly planned and analysed. This is to prevent unplanned failure and to effectively execute planned maintenance.

6.2 Leadership

The top management comes from OOW. They need to be involved in the planning, implementation, and operation of the maintenance strategy. This includes a policy with clear guidelines for the project. [35, p. 2]

6.2.1 Technical hierarchy

The policy includes guiding principles for asset management activities [35, p. 3]. A technical hierarchy shows guidelines for how equipment should be sorted on the WT.

A simplified technical hierarchy was developed in figure2 and figure 6 to provide an example. The WT should be divided into substructure and topside.

6.2.2 Criticality

The policy should include clear guidelines for what criticality is. Once the various parts of the WT have been established within the technical hierarchy, reliability data can be collected from these components. This data makes it possible to determine the criticality of different parts.

The Reliawind project ran from 2008 to 2011, and the aim was to identify and understand critical failures and their mechanisms for WTs [40]. They performed this project using quantitative studies of detailed wind farm data. Results from this project contains 240 months of data from 290 WTs. To be able to compare all the WTs, they created a standardised taxonomy. Examples from this are shown in figure 28. [41]

System	Sub-System	Assembly	Sub-Assembly	Part
Turbine	Rotor	Electrical pitch	Pitch motor	Brush
Turbine	Drive train	Gearbox assembly	Gearbox	Stage 1 planetary wheel
Turbine	Power	Generator assembly	Rotor	Rotor winding

Figure 28: Example from the reliawind turbine taxonomy[41, p. 3]

In the Reliawind report, data from failure rates and downtime are presented [41]. The following charts in figure 29 and figure 30 present the results from the report. The Deepsea Star turbine that OOW is designing is a 15 MW WT. Since this is the largest turbine on the market, there is not much operational data from 15 MW WTs. This means that the numbers from the Reliawind report are not applicable for the GoliatVIND project. Still, this report is useful to get an idea of what challenges may appear.

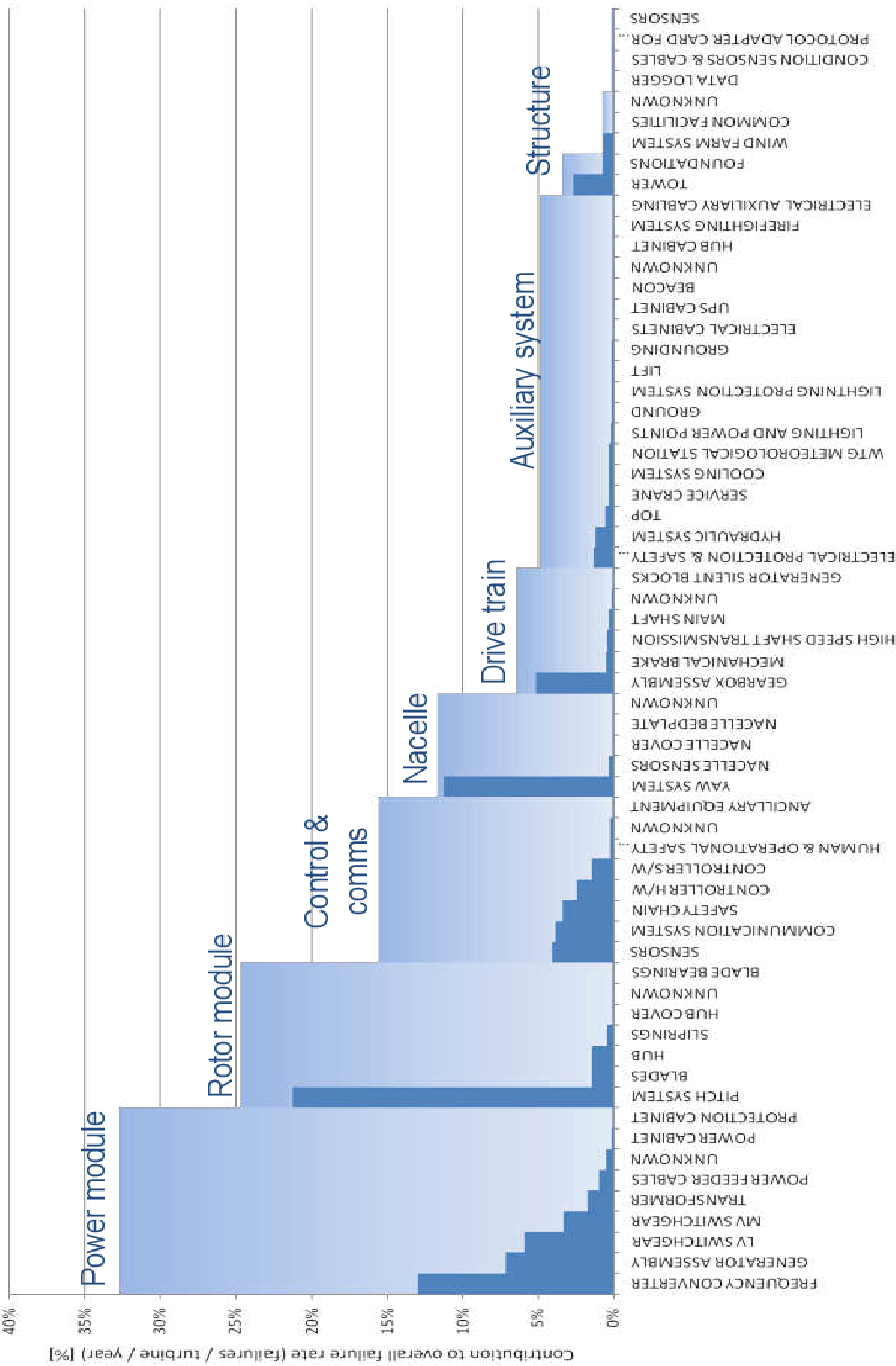

Figure 29: Normalised failure rate for WT of multiple manufacturers[41, p. 6]

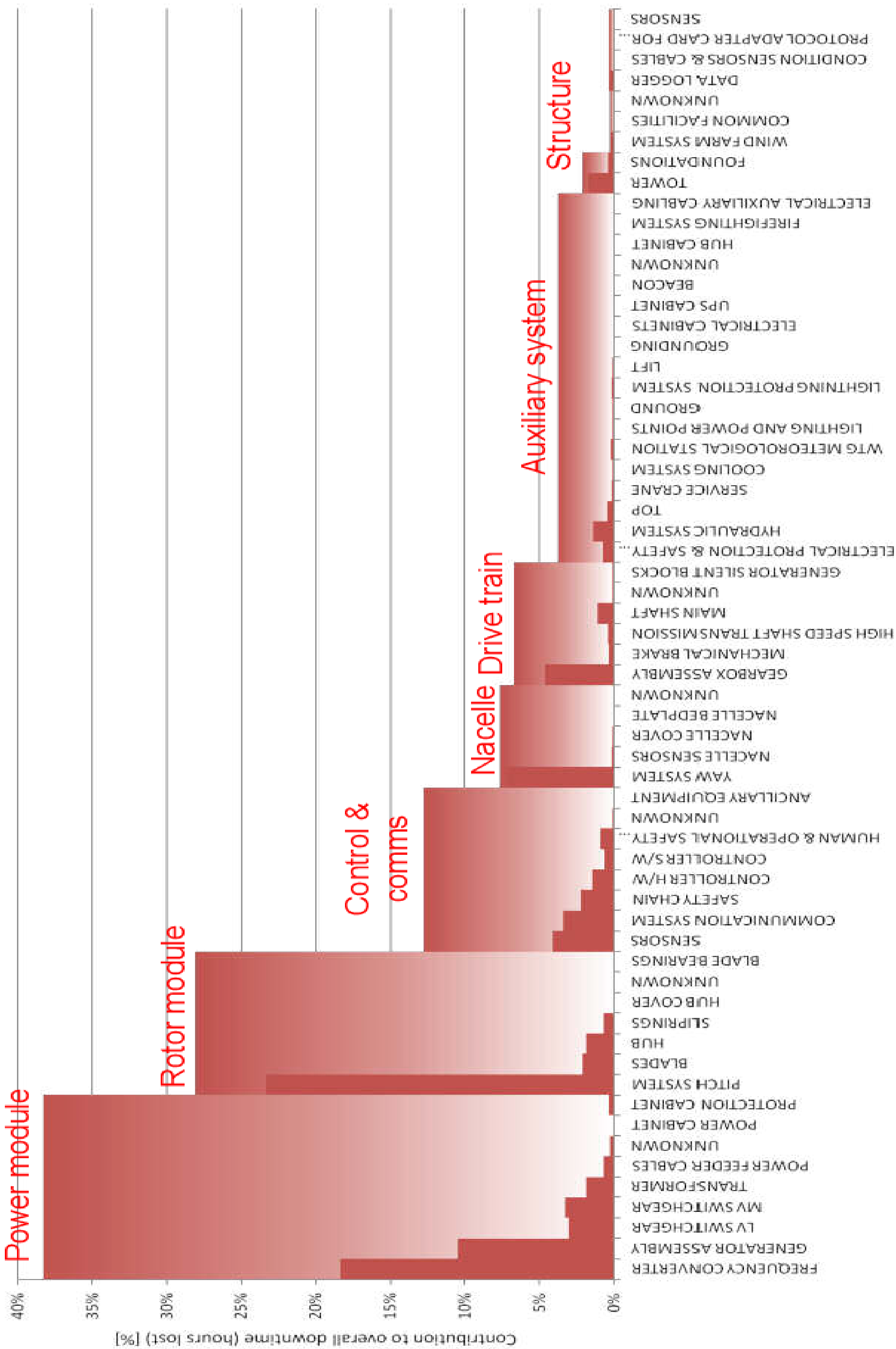

Figure 30: Normalised hours downtime per turbine per year of multiple manufacturers[41, p. 7]

The results from these figures show that among the components that fail and significantly contributes to downtime are the frequency converter, generator, pitch system, and yaw system. From these results it is possible to determine the criticality of different parts of the WT. To determine this, the most common technique is to use a risk matrix. The risk matrix shows the consequence (severity) against the probability. The consequence class can be regarded in three categories: Safety, environment, and business [42]. Regarding downtime, it categorises under the business category. At OTL they perform various types of risk evaluation. All risk matrices are based upon a 5x5 level 1 risk matrix. Risk matrices in higher levels are based upon the same criteria as the level 1 matrix. The risk matrix used for maintenance is a 3x3 level 3 matrix. If it follows the pillars, the matrix can be changed to fit the project better. OTL uses an incident classification matrix, about downtime and material damage. This uses the probability multiplied with criticality to determine the risk classification.

PoF Ranking	PoF Description	A	B	C	D	E
5	(1) In a small population, one or more failures can be expected annually. (2) Failure has occurred several times a year in the location.	YELLOW	RED	RED	RED	RED
4	(1) In a large population, one or more failures can be expected annually. (2) Failure has occurred several times a year in operating company.	YELLOW	YELLOW	RED	RED	RED
3	(1) Several failures may occur during the life of the installation for a system comprising a small number of components. (2) Failure has occurred in the operating company.	GREEN	YELLOW	YELLOW	RED	RED
2	(1) Several failures may occur during the life of the installation for a system comprising a large number of components. (2) Failure has occurred in industry.	GREEN	GREEN	YELLOW	YELLOW	RED
1	(1) Several failures may occur during the life of the installation for a system comprising a large number of components. (2) Failure has occurred in industry.	GREEN	GREEN	GREEN	YELLOW	YELLOW
CoF Types	Safety	No Injury	Minor Injury Absence < 2 days	Major Injury Absence > 2 days	Single Fatality	Multiple Fatalities
	Envirnoment	No pollution	Minor local effect. Can be cleaned up easily.	Significant local effect. Will take more than 1 man week to remove.	Pollution has significant effect upon the surrounding ecosystem (e.g. population of birds or fish).	Pollution that can cause massive and irreparable damage to ecosystem.
	Business	No downtime or asset damage	< € 10.000 damage or downtime < one shift	< € 100.000 damage or downtime < 4 shifts	< € 1.000.000 damage or downtime < one month	< € 10.000.000 damage or downtime one year
CoF Ranking		A	B	C	D	E

Figure 31: Example of a risk matrix[42, p. 16]

From the interviews it was discovered that OOW defines critical parts as either equipment that has impact on safety, strategic parts that can reduce downtime or frequently failure components. Since this is the definition from OOW, the critical parts can be determined from looking at other projects, i.e. Reliawind. Based on this the critical parts would be the frequency converter, generator, pitch system, and yaw system. This will be seen in the risk matrix that OOW will develop.

6.3 Planning

According to the planning section of ISO 55000 all risks should be looked at. The risks should have a plan to reduce or remove the undesired effects from them. [35, p. 3]
It can be beneficial, especially for a WT, to utilize predictive maintenance as it reduces the need for visual inspections. ReliablePlant performed a survey, where managers and supervisors from over 20 industries were asked about their maintenance program. The survey shows that 76 % use preventive maintenance, and 65% uses predictive maintenance [43]. Regarding internet connected predictive maintenance, the survey also illustrates that 71% of the participants have a concern regarding the lack of internal skilled personnel. This is an issue that needs to be addressed. According to current industry practices, the most beneficial solution for a WT is to utilize a combination of preventive and predictive maintenance. [43]

6.3.1 Reliability Centered Maintenance

Both OTL and OOW states in the interview that they want a RCM-based approach, which is an action to address risks and opportunities. This approach is something that especially OTL has great experience with.

There are several advantages of implementing a RCM analysis. Implementing a RCM contributes to increased efficiency by preventing time-consuming and unnecessary maintenance actions, eliminating failures and optimizing the asset. [44]

By not overspending on unnecessary maintenance while preventing major breakdowns, RCM reduces cost. It also reduces cost by removing unnecessary spare parts. A well-executed RCM helps set reasonable expectations in budgeting by giving information on the upkeep required in the lifetime of the equipment. Thus, making an effective maintenance schedule which shows future asset replacements required. [44]

RCM improves the productivity by systematising the maintenance, and therefore saving time implementing new information and other documentation. RCM will lead to less downtime for the asset, and therefore better productivity. [45]

RCM does not consider the maintenance cost of the asset, nor the cost of owning the asset. This need to be investigated with other analyses [45]. The RCM is limited by the resources that are available. Additionally, the RCM process is a time-consuming process, and there needs to be trained personnel to execute the analysis. All these factors leads to RCM being costly in the startup phase. [45]

The input data limits the output of the RCM. Input data are often failure rates, potential failures, root causes of failures and other operational data. In a starting phase, the input data is often limited, thus making the RCM less reliable. When the asset has been in operation some time, the RCM becomes more reliable.

6.3.2 Condition based maintenance

If CBM is integrated into RCM it will improve maintenance decisions by providing real-time data on equipment health. The DNV standard [46] specifies that CBM should only be applied to specific functional failure modes determined from the RCM analysis. The failure modes where CBM can be applied needs to be able to detect degradation with sufficient lead time. The lead time needs to be long enough to implement necessary maintenance tasks before reaching failure. Figure 32 demonstrates the survey arrangement of CBM. [46]

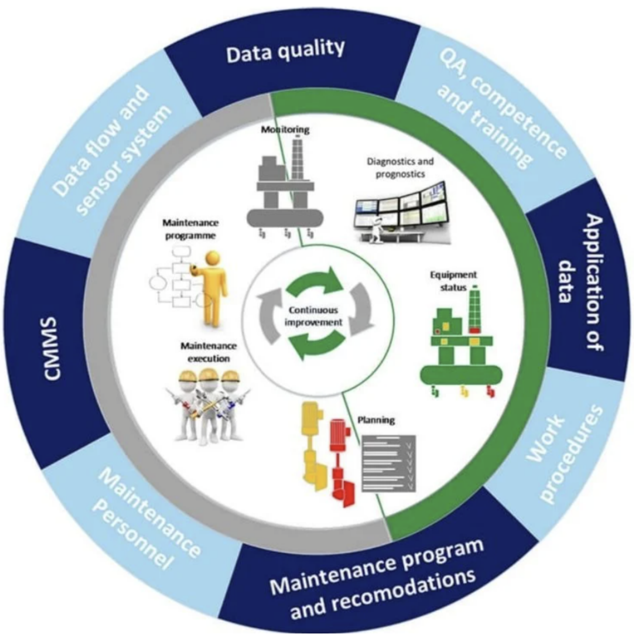

Figure 32: Survey arrangement CBM [46]

Since there is limited access to the FOWU a CBM approach becomes essential for effective asset management. Additionally, CBM ensures continual improvement of the maintenance plan. Still, it needs to be considered that the sensors may need maintenance as well.

6.3.3 Maintenance interval

ISO 55002 states that the organization should determine and plan actions to address its AMS risks [33, p. 8]. To do this, a maintenance plan is necessary. The OEM have guidelines for how often maintenance and inspections need to be performed, but it is also important to be aware of what the different standards and regulations require. DNV-RU-OU-0512 is a standard from DNV on floating wind installations. According to DNV-RU-OU-0512 the FOWU needs to have an annual survey [47, p. 65]. This is to confirm that the installation complies with requirements and is in satisfactorily condition. This survey will mostly be done on-site, provided that the right conditions are met. If it is a visual inspection, a drone or helicopter can be used. Submerged equipment will also be included in the survey. If underwater inspections are required, they should be done in accordance to approved procedure, personnel, and equipment. More details can be found in the DNV-0512 standard. [47, p. 65]

OOW is planning to make a semi-submersible WT. This makes the structure have more movement than i.e. onshore a WT or a WT that is bottom fixed. The fixed offshore WT can withstand harsh weather conditions, due to it being directly fixed to the seabed [48]. The movement of the semi-submersible WT leads to difficulties in when the maintenance tasks can be executed. To have the best conditions for the personnel to perform efficiently and safely, the sea needs to be as still as possible. Since the project is planned to be located in the Barents Sea, where there are harsh conditions, maintenance is preferred to be done during the summer season. This is important to have in mind when planning the maintenance intervals.

The intervals for planned maintenance will become more accurate as the WT operates over time. With increased operation, the RCM gathers more data.

6.3.4 Spare part evaluation

A spare part evaluation will reduce undesired effects of a risk and participate to achieve continual improvement. In case of unplanned events, it is essential to have executed a spare part evaluation to minimize downtime.

Operational spare parts and consumable spare parts are necessary to be located on a near land base. The capital spare parts can be stored at a warehouse further away. This could i.e. be where the WT are manufactured. When OOW have enough accurate data, the capital spare parts could be ordered when they are needed.

6.4 Support

OOW needs support to have an effective maintenance strategy. A supply chain for maintenance equipment is essential. A CMMS will help to structure the information and make it easy to update with new information. A gap analysis will help map competence and resources. For the WT, personnel with special competence are needed.

6.4.1 Supply chain management

ISO 55001 states that ”the organization shall determine and provide the resources needed for the establishment, implementation, maintenance and continual improvement of the AMS ”[35, p. 13]. For this statement to be fulfilled a proper supply chain is necessary. This can be achieved by proper supply chain management. Supply chain management is the ”management of flow of goods and services to and from a company and includes all of the processes involved in transforming raw components into final products” [49]. The supply chain follows the materials/ components from start until finished product and investigates each step where value can be added or become more efficient. There are different kinds of supply chains, and the company should investigate which type is most applicable for their goals. [49]

6.4.2 Communication

Both internal and external communication are important according to ISO 55001 [35, p. 16]. Clear guidelines for communication are important. According to the interviews OOW currently uses Aconex as a communication platform. In the phase they are in right now, designing and developing a supply chain, Aconex fulfils their needs. In later phases, such as the detailed engineering phase, a new communication platform might be necessary. The communication between suppliers/contractors will be important in this stage. The information from the communication platform needs to be collected and transferred to the CMMS. This could be done by using an application programming interface (API). An API is a way to integrate a communication platform such as Aconex to another application, e.g. a CMMS [50].

6.4.3 Computerized maintenance management system

ISO 55002 states that the organization shall consider the information requirements related to areas like strategy and planning, technical, physical asset properties, and more [33, p. 16-17]. This can be structured in a CMMS. From the interview with OOW it became clear that in the detailed engineering phases OOW wants a CMMS that collects design, engineering, fabrication and commissioning data, including maintenance recommendations from suppliers. In future states OOW needs the CMMS to gather data and information from the suppliers. The data gathered from different suppliers/contractors should be easy to put into the CMMS.

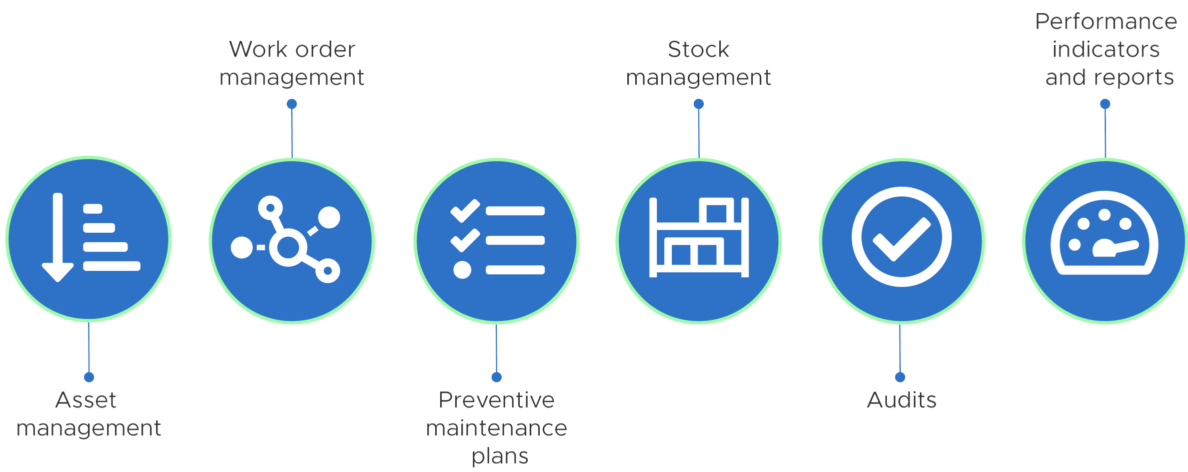

Figure 33: Main functions of CMMS [51]

Artificial intelligence (AI) is a great tool for sorting data and finding trends. It is commonly used in predicative maintenance. With accurate predictions the operational efficiency is increased and unplanned downtime is reduced. By providing accurate predictions it contributes to preventing equipment failure. AI can process a huge amount of data in a short amount of time, which can help to get more accurate predictions. It is a great tool for inventory management as well. The AI systems can identify patterns in part usage and purchase history to give a recommendation on when parts should be restocked. [52]

6.4.4 Computerized maintenance management system selection

There are several different types of CMMS. OTL uses IBM Maximo and IFS Applications. IBM Maximo consists of applications for asset monitoring, management, predicative maintenance, and reliability planning [53]. IFS Applications is an enterprise resource planning (ERP) program that manages the day-to-day business of a company. It integrates functions like supply chain, manufacturing, engineering, maintenance, projects, human resources and more into one software. [54]

To decide what CMMS is best suitable for the WT a comparison between the two can be performed. OOW wants a RCM approach for their maintenance strategy. It is therefore crucial that the system have a RCM-module that is easy to apply. Technology Evaluation Centers did a comparison between the different CMMSs. When it comes to reliability IBM Maximo is slightly ahead. It stands out in areas such as failure analysis, root cause analysis and reliability centered maintenance. [55]

Both IBM Maximo and IFS Applications uses AI in their system. Maximo does this by monitoring the assets and notifying the users when the assets are not performing as expected. When data is collected over time, the program will be able to identify degrees of failures and connect them to causes. When work and requests are logged the AI learns more and becomes better at providing predicative maintenance. [56]

In IFS Applications AI is used to automate tasks and make the process more efficient by removing unnecessary steps. AI does this based on behaviour across operations. This increases the efficiency and reduces costs. [57]

6.5 Operation

When executing the maintenance there are several things to consider. It is necessary to document the actions, and to assess and manage ongoing risks. Some actions which OOW does not have the competence and resources for should be outsourced, especially in a starting phase. A typical example is specialized technicians needed to do maintenance on the WT. [35, p. 8-10]

6.5.1 Standard procedure and job safety analysis

Maintenance operations frequently done should have a documented standard procedure. All standard procedures should be in a joint document register and have a risk analysis and clear instructions of the operation. If the operation does not have a standard procedure, a job safety analysis is necessary before starting the work. [58, p. 25-26]

6.5.2 Means of transportation

To execute maintenance actions on the FOWU a way of transportation is necessary. GoliatVIND are located approximately 85 kilometres northwest from Hammerfest and are therefore in need of transport of personnel and equipment. [14]

A means of transport is to use a vessel with access system to the FOWU, which is a vessel that has all the systems needed to operate an offshore wind farm. This can be an oil field support vessel, which have a dynamic positioning and a suitable access system to access unmanned offshore platforms. In the example used in ”Offshore Wind Turbines. Reliability, availability, and maintenance” the vessel has a crew of 18 and with space to 68 additional personnel if necessary[28, p. 147]. Calculations for hourly cost of maintenance with the vessel are made in the book. The calculations assume that there are four crews working 12-hour shifts and covering two WTs at each shift change. The calculations shows that the cost per hour O&M work is 393 pounds. [28, p. 147-148]

Helicopters are another way of transport used offshore. A helicopter can transport personnel, spare parts, and equipment. Based on calculations in ”Offshore Wind Turbines. Reliability, availability and maintenance” the cost per hour of helicopter O&M work is 1200 pounds with a seven-seat helicopter and flight time. [28, p. 150]

Another solution for transport is drones. The price for drones varies after type and what trained personnel is needed. Drones can transport lightweight spare parts and equipment. This is written about in subsection 6.5.4

It is possible to combine the use of helicopters and vessels. This will most likely be the optimal means of transportation. In the book ”Offshore Wind: Future of logistics” two solutions are presented. In the first solution, the personnel are transported by helicopters everyday with the substation as an offshore base. This requires the substation to be designed to handle personnel. The cargo is transported by a barge once every two weeks prior to maintenance. This lowers the cost of personnel because of a shorter transit time and a lower number of technicians. The cost of logistic will also be lower since the barge will only be used a few days per month. The WT will have less downtime because equipment will already be stationed, and personnel uses helicopter which saves time. [59, p. 13]

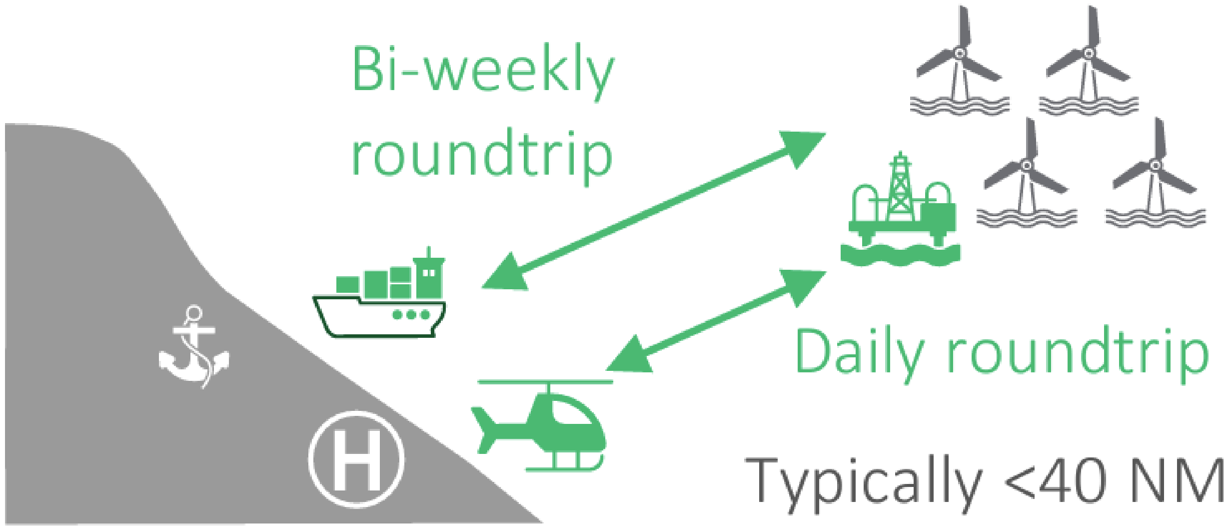

Figure 34: Helicopters and barges [59, p. 14]

The second solution is to use helicopters, vessel with access systems and a daughter craft. A daughter craft is a vessel used to transport personnel. The vessel with access system is used for scheduled maintenance with the technicians aboard, and the helicopters and daughter crafts are used for troubleshooting and will always be available. For this to save costs the means of transportation needs to be distributed on several wind farms or an oil and gas site combined with the wind farm. The vessel will be operating nine months per year, and the use of helicopter will be optimized to reach the lowest hour cost. This will lower the costs of personnel and logistics. This is because the personnel are offshore at all times and the utilization of vessels and helicopters are optimized. There will be less downtime cause of the permanent presence offshore of a daughter craft and quick response time for a helicopter. [59, p. 13]

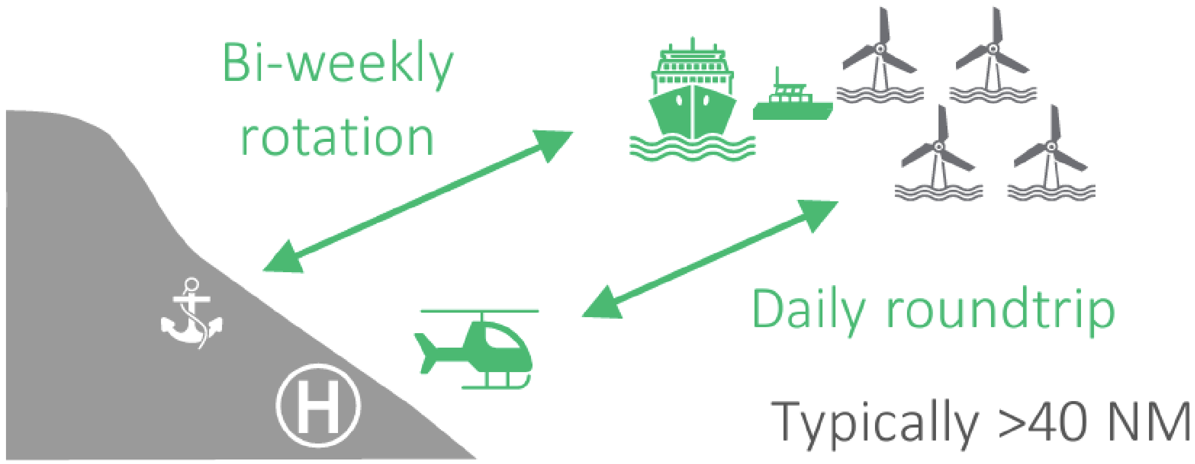

Figure 35: Vessel, daughter craft and helicopters [59, p. 14]

According to "Offshore Wind: Future of logistics"[59][p. 14] these two solutions can lead up to 30% financial benefits and up to 50% reduction in carbon emissions compared to the standard solutions already used. [59, p. 14]

If the maintenance categorizes as major component exchange, the FOWU will be towed to a land base with repair facilities. This is something that OOW defined in the interview. The land base can be the same place as where the FOWU was installed.

6.5.3 Challenges with logistics

GoliatVINDs WTs are located far from shore in a harsh environment. This leads to logistic challenges. Maintenance operations will rely on the weather and climate of the Barents Sea. It will be difficult to manoeuvre logistics safely in the winter season, and necessary maintenance might be delayed due to difficult conditions. [59, p. 19]

The offshore wind industry is not yet a lucrative industry. The industry relies on subsidies, and if the subsidies are reduced, the logistics need to be less costly for the WT to profit. This could be a future challenge for the industry. [59, p. 11]

Another challenge is that the company will be in competition with the oil and gas industry since they will use the same means of transportation. The oil and gas industry is a lucrative industry. They can push transportation prices up if there is significant competition. This can also lead to transportation methods being harder to obtain at short notice.

6.5.4 Drones in maintenance

Drones are an unmanned flying vehicle that are remotely controlled. This means that the drones could be controlled from the land base or from a nearby installation or boat. The drones can be used to inspect the blades and hull of the WT. When using drones for inspections, it is not necessary to have personnel on the WT. This saves cost of transporting personnel, and the personnel is not exposed to risk.

Drones can also be used to handle logistic. If the personnel on the WT are missing spare parts or equipment because of failed planning or unforeseen events, they must go onshore to get the equipment. Drones can be used instead of the personnel going onshore.

The drones are already slightly used offshore to deliver spare parts and equipment. Equinor have started using drones to deliver lightweight cargo to Gullfaks from Mongstad. This is a 180 kilometres long trip, where it is needed to change battery underway. The top speed of the drones Equinor uses according to the manufacturer are 200 kilometres per hour and can fly up to 175 kilometres with a 3 kilogram cargo, or 130 kilometres with a 5 kilogram cargo. [60]

The company Ørsted uses drones for logistics in offshore wind industry. They use a drone that can carry up to 68 kilograms. The drone is used to deliver cargo to the WT and to transport spare parts and equipment from the boat on site to the WT. [61]

According to Ørsted the transport of a spare part from the boat to the nacelle usually takes at least 30 minutes [61]. Using a drone instead saves time, reduces the need to sail to and from the WT and avoids use of crane. [61]

The use of drones reduces cost and increases availability by spending less time craning cargo and ensure timely delivery of missing spare parts and equipment. It reduces environmental impacts by not needing other transport to pick up missing equipment and reducing the need to sail to and from the WT. Drones improves operational safety and efficiency by not using as much crane operations, and minimising boat and helicopter time for the personnel. The drone can eliminate the need to shut down the WT when delivering cargo, thus making the WT more effective and get more availability. [61]

6.6 Performance evaluation

ISO 55001 states that ”the organization shall determine what needs to be monitored and measured” [35, p. 8], and the methods to ensure valid results. It is also stated that internal audits shall be conducted at planned intervals, and that top management shall review the AMS to ensure the suitability, adequacy, and effectiveness. [35, p. 9]

The WT is essentially an unmanned remote power unit. This type of unit requires several monitoring systems in place to function. Additionally, OOW requires everything to be managed from land, which means a high requirement for new technology and monitoring.

6.6.1 Supervisory control and data acquisition

SCADA is favoured in the renewable energy sector because it allows remote monitoring. This is a benefit for offshore wind farms given the remote location. It is an expensive and an extensive operation to access the WT and perform maintenance on it. [27]
SCADA is generally a low-cost monitoring system. A challenge with SCADA is the large amount of output data from the WT. Fast-changing or valuable signals can be monitored continuously, i.e. wind speed and power output. The rest of the signals are normally sampled every 10 minutes. For an offshore wind farm each WT samples about 40 000 data items every 10 minutes. The data is mainly output signals, but some of the data is from the WT to the control room. This is equal to around 96 MB data every day. A software program is required for interpretation of the data. [28, p. 116-117]

The system can provide warning signs of approaching failures in the WT. According to ”Offshore Wind Turbines. Reliability, availability and maintenance” the monitored signals usually include:

- Active power output (and standard deviation over 10 minute interval)
- Anemometer-measured wind speed (and standard deviation over 10 minute interval)
- Gearbox bearing temperature
- Gearbox lubrication oil temperature
- Generator winding temperature
- Power factor
- Reactive power

- Phase currents
- Nacelle temperature (1 hour average)

[28, p. 225]
It allows operators to take maintenance or repair actions to prevent downtime or failures. The power output shows the production from the turbine. If this is a low number, it is a sign that something is wrong. The turbine is shut down in high wind speed to prevent wear and breakage. This could not be possible without knowledge of the wind speed that is monitored in the SCADA system. The bearing and lubrication oil temperature of the gearbox is also important to monitor to avoid overheating. It is also important to monitor the lubrication oil temperature to keep the viscosity stable [62]. The generator winding temperature is monitored to get an early detection of insulation breakdown and overheating [63]. The power factor demonstrates the efficiency of the WT. In a lot of regions, a power factor below 95% is considered inefficient [64]. If the power factor is low, energy is being wasted. To emphasize how much energy is wasted, reactive power is monitored. Phase currents is monitored to detect possible defects in the electrical system. The nacelle temperature is monitored to detect overheating of the critical components that is located inside the nacelle.

The data from the SCADA system is essential. However, for the FOWU to function, high resolution monitoring signals such as CMS is necessary.

6.6.2 Condition monitoring system

CMS monitors different parts of the WT. This can contribute to optimized asset performance and less downtime by alerting potential failures. The CMS should provide long enough lead time to allow sufficient time for implementing preventive maintenance tasks. It is important to evaluate the data from the CMS to prevent failures.

Vibrations are used to monitor the generator, gearbox, main bearing, tower, and blades of the WT. Accelerometers and proximeters are used to measure the vibrations, and detects specific frequencies related to the structure. This method can detect structural damage in the blades or tower, pitting in bearings and wear in the gear teeth. The vibrations need to be analysed to detect faults. [65, A-4],[28, p. 118-119]

To prevent gearbox failures the CMS analyses gearbox oil debris. The oil provides cooling and lubrication for the gearbox and the meshing gears. To maintain the oil, the removal of debris, temperature control and renewal of the oil are essential. Ferrous and non-ferrous debris is unavoidable since the gears and bearings will wear over time. Large gearboxes will use a spray lubrication system. This system mixes the oil stream, thus making it universal and perfect for condition monitoring. Oil debris counters detects and counts different size particles in a portion of the oil. The data from the oil debris counter is input to the CMS. To prevent failure, the oil debris detection must give a warning long before potential failure occurs. [28, p. 119-120]

Strain gauges can be incorporated in foundations, moorings, and cable systems above water to measure strain in the structure. The measurement can identify structural damage and fatigue. Fibre bragg gratings strain gauges in the WT blades makes a bending moment measurement. This measurement is mainly in use to ensure blade pitch controls but is also in use to condition monitor the WT performance. [65, A-6], [28, p. 121]

The electrical signals, voltage, current and power used to control the generator speed have been used for condition monitoring electrical machines for several years. These signals can now be adapted to the WT drive train, to be used as global monitoring signals. [28, p. 121]

The subsea cables incorporating fibre optics, can use the fibre optic to find structural damage, degradation, and aging in the cables. This is done by using reflectometry over a time domain and observing abnormalities in the reflectometry. The fibre cables have a distributed temperature measurement which can detect overheating and insulation damage. The system works by using the change in optical signal to determine the temperature of the fibre optic, and therefore determining the temperature in the cable. [65, A-5]

To reach the full potential of monitoring the WT there are some challenges regarding the integration of the two systems: SCADA and CMS. The SCADA system is often integrated into the controller of the WT, while the CMS is purchased separately and installed independently of the WT's controller. This makes it difficult to incorporate the two into the same program. Still, it is possible to do using a HMI but this requires technical expertise. [28, p. 137]

6.6.3 Gap analysis

According to ISO 55001 ”the top management shall review the organization's asset management system at planned intervals to ensure its continuing suitability, adequacy and effectiveness” [35, p. 9].

To ensure that this is achieved, a gap analysis can be carried out. A skill gap analysis and a strategic gap analysis is the most relevant for evaluating the performance of the organization.
After a skill gap analysis is done, the result may lead to needing to outsource activities because of lack of competence and resources.[31]

6.7 Improvement

Improvements are a important part of ISO 55000. Continual improvement ensures that the assets remain reliable and effective over time, while elevating overall asset performance. It is important to implement changes based on the performance evaluation when necessary.

6.7.1 Synergi

ISO 55001 states that when a nonconformity happens, actions must be controlled and corrected. Then the consequences must be addressed. According to the standard it should be checked whether similar nonconformities exist. [35, p. 10]

A software where nonconformities are gathered is utilized to make this process easier. Synergi Life is commonly used for risk management, and from the interviews it was discovered that it was used internally at Odfjell[66]. It helps organizations ”implement coordinated programs of risk management with appropriate risk assessments, risk response strategies, controls and key performance indicators”[66].

6.7.2 Reliability centered maintenance

According to ISO55001 ”the organization shall establish processes to identify potential failures and evaluate the need for preventive action” [35, p. 10]. This can be done by evaluating the data from the CMS and SCADA and adjust preventive maintenance intervals. The adjustment can be determined by conducting a RCM analysis. When conducting the RCM analysis after the asset have had some operational time, the results will be more reliable than in the startup phase. Thus, it is important to make improvements in accordance with the results of the RCM. Especially, for the most critical assets it is important to implement a RCM approach to enhance asset performance and reliability. To make it easier to systematize the RCM analysis, the data can be structured in a CMMS. The CMMS uses AI to provide predicative maintenance. AI monitors the asset and notifies personnel when the asset is not performing. In this strategy, CMS and SCADA will be used for monitoring. When the asset is not performing, the personnel will be notified, and can perform adjustments.

6.7.3 Root cause analysis

When an incident occurs ISO55001 states that the organization shall evaluate the need for action to eliminate the causes of the incident by among other things reviewing it [35, p. 10]. This can be done by carrying out a root cause analysis. A root cause analysis helps to find the cause of the failure in the WT. After discovering the root causes of an incident, actions to eliminate them shall be taken to ensure that similar incidents don't reoccur. The team should figure out which of the methods in chapter 2.5.2 suits them the most, and utilize them to discover the root cause and prevent future failures.

6.7.4 Gap-analysis

To achieve the organizational objectives, it is important assess the performance evaluation and identify gaps between current performance and the objectives. A gap analysis can also identify skill gaps and highlight the need for additional training or development. Results from the gap analysis can also help allocate resources and mitigate potential consequences of failure. [31]

7 Recommendations

For Odfjell Technology to be able to deliver a maintenance system to Odfjell Oceanwind there needs to be a clear maintenance strategy in place. We recommend using ISO 55000 to develop the maintenance strategy. All the requirements in the standards does not need to be covered but can be applied as a guideline for the strategy. Benefits of ISO 55000 is reduced maintenance costs, improved product quality, optimized return on physical assets and improved safety record. ISO 55000 does not tell the specifics of a maintenance strategy, such as what maintenance techniques to utilize, but sets a framework for the maintenance strategy. [67]

From the interviews there was gathered an impression that OOW wants the wind turbine availability to be 97,5%. We think this objective is unachievable. This is due to shut down of the WT when the wind conditions are not optimal or when there is no request for power. Additionally, there will be downtime when maintenance needs to be executed. ISO55002 states that ”asset management objectives should be specific, measurable, achievable, realistic and time-bound” [33]. Thus, we would recommend develping more specific maintenance objectives that are realistic and time-bound for GoliatVIND. One of the objectives should be related to collaboration with relevant stakeholders.

We recommend using the RCM-approach because it helps systematize the maintenance processes. It will increase efficiency and can help reduce the downtime. It is a well-established system that have good previous results. The organization has a lot of expertise regarding RCM-analysis. Thus, we recommend for OOW to utilize this expertise when developing the maintenance.

Since OOW demands everything to be managed from land we recommend utilizing condition based maintenance. This is something that is necessary to gain more knowledge about. The integrity department at OTL is working on doing analysis to find out what needs to be measured and what is not important regarding CBM. We recommend for OOW to utilize the competence OTL is developing regarding CBM. It is also beneficial to utilize the experience OTL and ODL have with harsh weather conditions, which is one of their main pillars.

During the interview, OOW stated that maintenance will be outsourced to the WTG supplier. We recommend this to be in accordance with ISO55000. According to the standard the organization should formalize the relationship, i.e. through a contract. It is also important that outsourcing is controlled by the organization to ensure the performance is as planned [33].

Regarding transportation to the FOWU, we recommend using a combination of helicopter, vessels with access systems and a daughter craft for transporting personnel and equipment to the FOWU in the future. This provides a safe and efficient way to transport personnel and equipment. It is a cost-effective method if OOW gets the opportunity to collaborate with multiple parties regarding ownership of the transport methods. If collaboration is not possible, we recommend using helicopters for personnel and light equipment. For bigger equipment a vessel is necessary.

We recommend gaining knowledge from other similar projects both onshore and offshore. An example of a project that can be taken into consideration is the Reliawind project which is discussed in chapter 6.2.2. Analysing methodologies and solutions utilized in other projects can provide valuable knowledge that can be applied to GoliatVIND and other future projects. Doing this will comply with requirements for continual improvement in ISO55000.

OTL uses two CMMSs, and it would be beneficial for OOW to utilize this competence. When choosing a CMMS we recommend having the RCM-approach in mind. There are several similarities between Maximo and IFS ERP. It would be beneficial to try demos of the CMMSs, and evaluate what works best for the intended use.

8 Discussion

One of the challenges with creating the maintenance strategy was that there were no possibility to conduct interviews with OEMs. This led to a significant loss of information that could have been valuable for the maintenance strategy. There was also no opportunity to talk to the top management in Odfjell Oceanwind, which lead to a lack of information. The maintenance strategy had to be based on existing research and studies, due to a lack of availability of information from OOW. Since FOWUs still are relatively new technology, the amount of available qualitative data is limited. There will be similarities in the maintenance strategy for different FOWUs, but more specific information needs to come from OOW to ensure that their requirements are met. In further development of GoliatVIND it is crucial with sufficient communication.

From the interviews it was gathered an impression that CBM is something that is new for Odfjell Technology. Still, this is something that will be beneficial when developing the strategy for the FOWU. It is important to distinguish between the different parts of the FOWU when developing the maintenance strategy. It will not be beneficial to integrate CBM on all parts, and the parts without condition monitoring will need more conventional maintenance methods.

In the initial phase OOW is dependent on communication between different companies. This is challenging and time consuming to do for the first time in a relatively new industry.

By determining the criticality of different components and performing a RCM analysis on parts that are critical, the maintenance strategy ensure that the costs are minimized. Additionally, the RCM will help to preserve the lifetime of the FOWU. Condition monitoring and continual improvements will help the AMS adapt to surrounding factors and ensure a lifetime of 25 years. Performing preventive maintenance will minimize downtime and ensure reliable power production. However, solely relying on preventive maintenance can lead to unnecessary maintenance operations which CBM can prevent. With the current technology, it is not optimal to have CBM as the main solution and there will be a need for a combination of preventive and condition based maintenance.

Ensuring that the spare parts are available, will help to keep up the availability of the FOWU and ensure reliable power production. To minimize costs a solution is to avoid storing unnecessary spare parts. The spare part evaluation will help to reach the objectives.

Using the transport methods that we recommend will provide sufficient resources and ensure safe working conditions. To meet the objectives there still needs to be evaluations of the risks associated with the working conditions. There will always be a risk to work offshore due to harsh weather conditions and the remote locations.

9 Conclusion

Developing a maintenance strategy is a comprehensive task, which ISO 55000 can simplify. The standards provide a structured framework and explains what needs to be considered to best utilize the assets.

By integrating the RCM approach within the framework, wind turbine operators can improve asset management practices, increase reliability, and optimize maintenance costs. CMS data is input to the RCM analysis. The data makes it easier for personnel to identify potential failures, optimize maintenance tasks and improve asset reliability. CMS consist of complex analysis and challenging data integration. The limited access to the FOWU makes it necessary to look deeper into CBM, which can be applied to a RCM analysis. CBM requires competent technicians to analyse the data.

To develop the maintenance strategy, interviews were conducted. Prior to the interview a hypothesis was outlined in chapter 5.1. In the hypothesis it was stated that several procedures from OTL could be utilized in the GoliatVIND project. This is shown to be correct by utilizing the RCM approach, which both interviewees wanted. There was also an expectation that preventive maintenance with a different approach is beneficial, which both OTL and OOW stated. Still, it appeared from the interviews that there were different expectations between OTL and OOW, especially in the handling of when major components will fail.

This thesis shows an example of how a maintenance strategy can be structured. Moving forward, OOW needs to apply the outlined maintenance strategy to make a detailed maintenance plan for the FOWU.

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Appendix

Appendix A: Drawings

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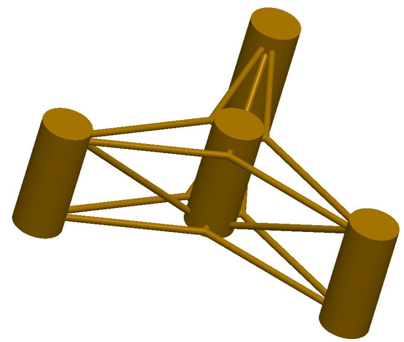

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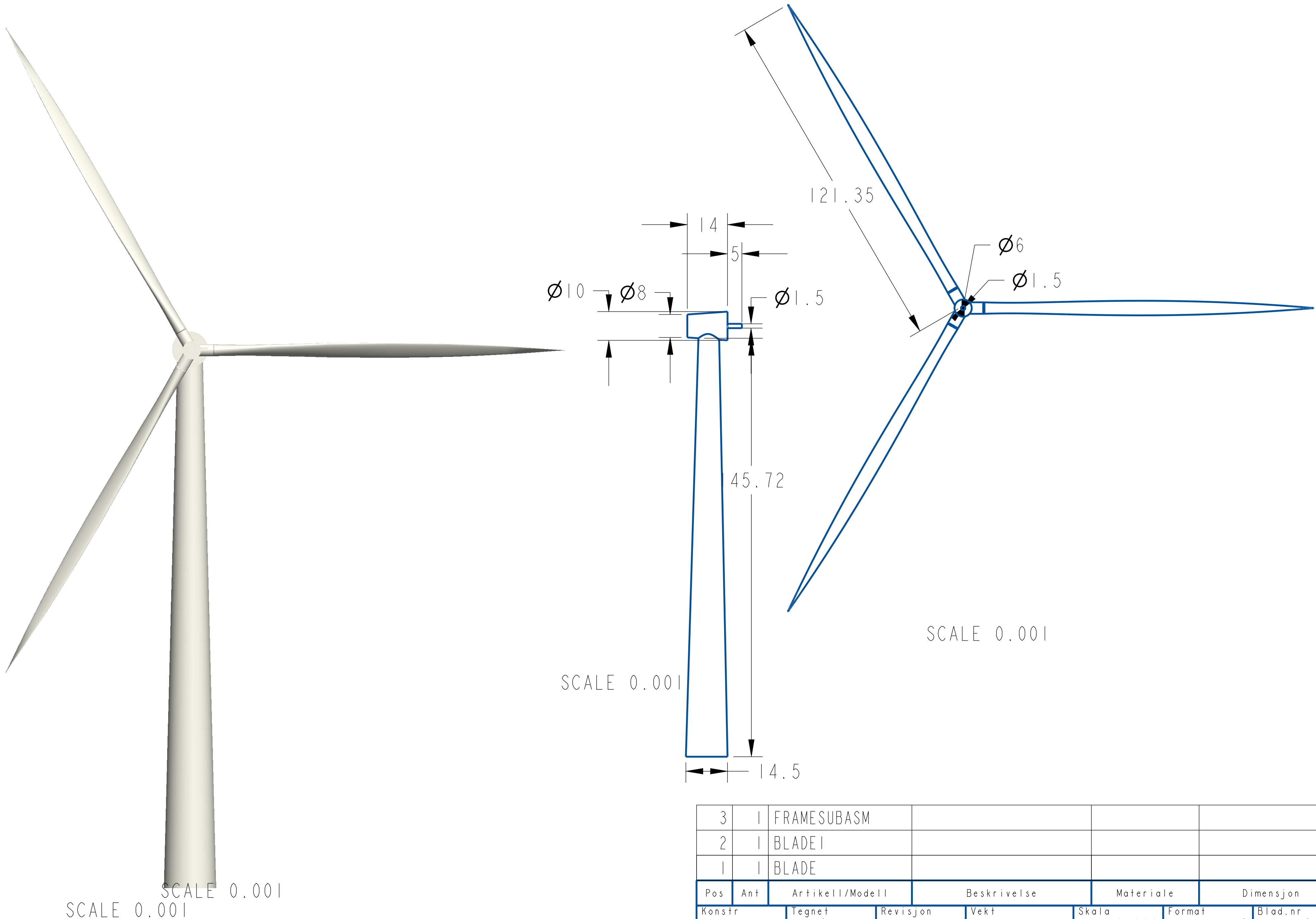

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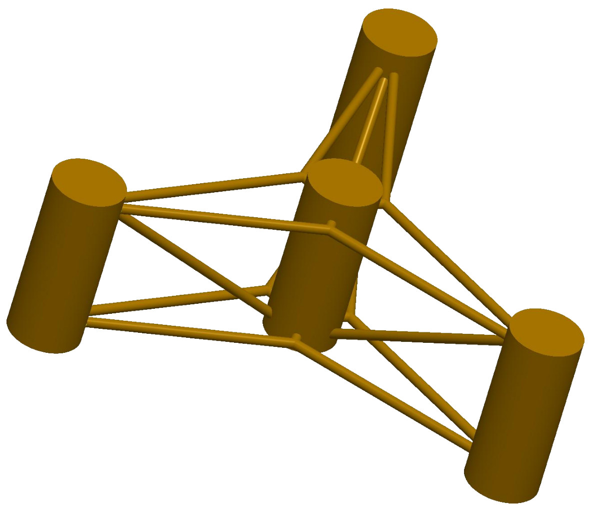
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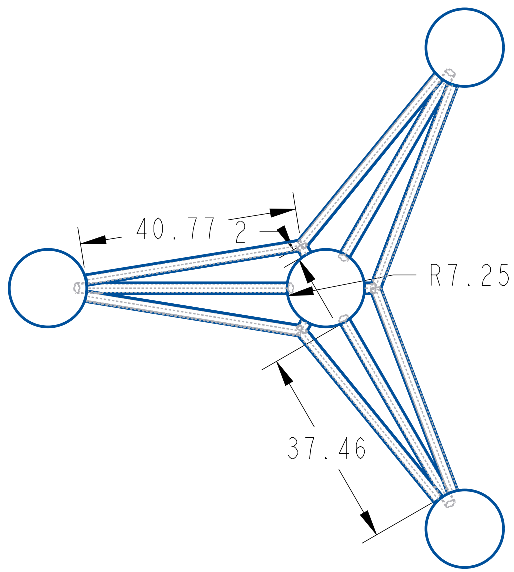

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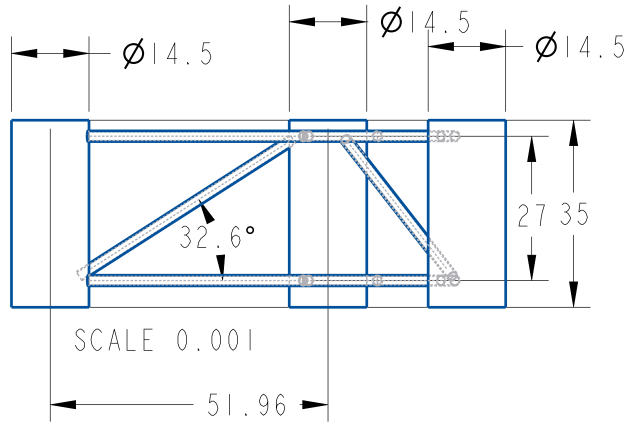

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