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Risk-based Maintenance and Smart Maintenance Concept For Offshore Wind Turbine: A study of reference wind turbine model

By

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Abstract

The wind energy sector is the highest trending renewable energy globally, both onshore and offshore. However, the potential for onshore wind power is limited due to some factors, such as land constraints and capacity factor. In contrast, Offshore wind power remains one of the most up-and-coming renewable energy sources. High rate of energy demand, energy security, vast ocean space, and the effort to reduce CO2 emission are some factors propelling the growth of the offshore wind market. As much as the offshore wind can harness more wind resources due to the stronger and consistent wind off the coast, it also increases equipment failure rate, cost of operation & maintenance(O&M), and safety risks associated with maintenance activities. Operation & maintenance is the leading cause of wind turbine downtime, and it is estimated to cost between 20% -30% of the Levelized cost of energy. Although O&M for offshore is still at the early stages compared to the oil & gas sector, it is regarded as a crucial aspect in the development phase. Trying to figure out the best possible way to improve O&M to reduce cost and mitigate other challenges remains a pressing question for wind farm owners and operators. Some Smart technologies applicable for offshore wind maintenance have been identified. One such technology is the digital twins model enabling real-time monitoring of the asset, using an autonomous Drone, Robotics for inspection and repairs, applying machine learning, and big data analytics to enable asset failure prediction and maintenance optimization. However, another puzzling question is how and where to begin?. Additionally, there are no studies on the adoption of Smart maintenance for offshore wind turbine equipment.

Therefore, the purpose of this thesis is to develop a baseline maintenance concept and illustrate how Smart maintenance concept can be applied to the offshore wind sector. Smart maintenance can be described as integrating technology, machines, and humans to build an intelligent and improved maintenance system. By effectively using the Condition Monitoring system (i.e., aided by Big data analysis, machine learning) and the combination of modern autonomous technology, decision alternatives can be optimized to adequately managed maintenance activities.

In order to achieve the aim of the thesis, several maintenance engineering steps were adopted, and these steps follow the risk-based maintenance approach (Base on Norsok-Z-008). This risk-based maintenance approach consists of Technical hierarchy, Functional hierarchy, Consequence classification, FMEA, and Maintenance selection/ Manning study. A reference direct-drive turbine model was studied in order to develop a technical hierarchy of the system where the equipment and maintainable items were grouped according to their hierarchy level using the 1SO 14224 standard. The functional hierarchy and consequence classification were developed to determine the criticality level of the main function and sub-function of the wind turbine equipment (i.e., low, medium, or high criticality). The failure mode and effect analysis (FMEA) was adopted to further analyze high and medium-level critical equipment by defining the root cause of failure in order to focus on the most critical failure mode. This process has enabled the development of the baseline maintenance concept for each selected critical failure mode.

Consequently, this thesis has provided new original knowledge for offshore wind application. It shows that the Risk-based maintenance approach can be transferred from the oil & gas sector to the wind sector as long as it considers the difference in risk-related issues (safety, environment) and takes into account the additional equipment that is not in oil & gas, such as the blade. However, to implement it more efficiently, there is a need for good risk evaluation criteria, reliable failure data

(MTTF, MTBF, failure mode), and expert opinion to define special functions. Moreover, the Smart maintenance concept can be integrated into the risk-based maintenance approach at the latter stage. Furthermore, this thesis has developed a Smart maintenance decision workflow to improve the maintenance operations for the offshore wind turbine. The workflow consists of three scenarios [1] Design-out scenario, [2] Condition monitoring scenario, [3] Autonomous solution scenario. These scenarios illustrate the steps, decision processes, and actions involved in implementing smart maintenance concepts for offshore wind turbine equipment. However, it will require implementing multiple scenarios to achieve the full benefit of the Smart maintenance concept.

Nevertheless, this thesis suggests that using autonomous solutions such as drones and repair robotic for some wind turbine maintenance activities such as for blade maintenance might have the potential to increase the availability by 39.83% and reduce safety risks associated with maintenance. It can also reduce total manning hours by 60.16%, which will decrease the maintenance cost eventually. Moreover, using autonomous drones and repair robots is not yet fully automated; it still requires the presence of about two technicians due to technical and safety-related issues.

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Francis Makua Udoh
Stavanger, June 15, 2021

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List of abbreviations

AUV	Autonomous Underwater Vehicle
CMS	Condition Monitoring System
CTV	Crew Transfer Vessel
DD	Direct-Drive
FH	Functional Hierarchy
FMEA	Failure Mode Effect Analysis
IMR	Inspection, Maintenance and Repair
IRENA	International Renewable Energy Agency
LCOE	Levelized cost of energy
MTTF	Mean Time to Fail
MTTR	Mean Time to Repair
O&M	Operation and Maintanance
OEM	Original equipment manufacturer
OREDA	Offshore and Onshore Reliability Data
OWF	Offshore Wind Farm
OWT	Offshore Wind Turbine
PHM	Prognostics and Health Management Technologic
RBM	Risk Based Maintenance
ROV	Remotely Operated Vehicle
SM	Smart Maintenance
SOV	Service offshore Vessel
SPARTA	System performance Availability and Reliability trend analysis
TH	Technical Hierarchy
UAV	Underwater Aerial Vehicle
WT	Wind Turbine

Chapter 1

1. Introduction

This chapter presents the holistic view of the offshore wind industry, the current market trend, and challenges faced in operation and maintenance. It also presents the main objective of this research, the scope of work, the research question, and the proposed methodology.

1.1. Background

The wind energy sector is the highest trending renewable energy globally, it includes both onshore and offshore, but the potential for onshore wind is limited due to land constraints and capacity factors. In contrast, Offshore wind power remains one of the most prospering renewable energy sources, which could reach over 120,000GW in production at maximum potential. Denmark installed the first offshore wind farm back in 1991, but the industry did not see much progress at that time due to expensive operational costs, logistics, and technological challenges. Currently, only 0.3% of global power generation is provided by offshore wind energy; however, it has a broad potential and is set to expand in the coming decades significantly (IEA, 2019). The “2019 future of wind report” from the IRENA (International Renewable Energy Agency) presented the development of offshore wind power as illustrated in Figure 1. It shows that by 2030, the total installed offshore wind capacity will rise to 228GW and will further increase to about 1000GW by 2050, which means about 17% of the total world installed wind capacity and reflecting a CAGR of 11.5% that is below the CAGR of 38.5% (IRENA, 2019).

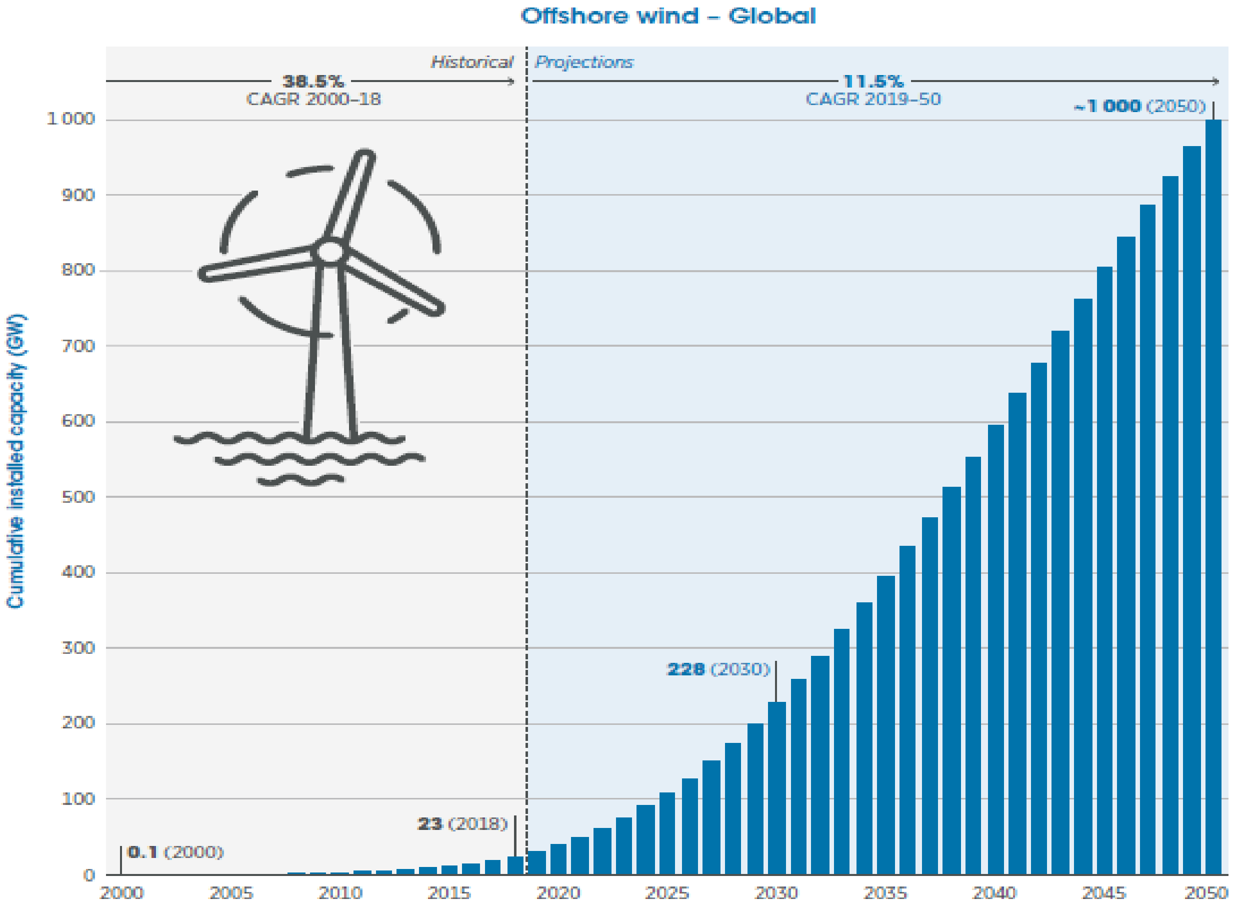


Figure 1. Future growth of Offshore wind power deployment (IRENA, 2019)

The factors propelling the market growth include the high rate of energy demand, energy security & access, high power generation capacity, vast ocean space, and the drive toward lowering the CO2 emission levels. The north-sea and the nearby Atlantic Ocean has over 90% of the world's installed offshore wind capacity. Most countries in Europe bordering the North-sea continue to witness significant growth in the offshore wind industry. This is due to adequate wind resources and good conditions for offshore wind technologies (IEA, 2019) provided by the shallow North and Baltic sea levels, where water depths can be less than 30 meters (Musial & Butterfield, 2004). About 77% of the cumulative installed offshore wind farms are in the North-sea (16,908MW), while the Irish sea and the Baltic sea holds 13% and 10%, respectively, i.e., 2,930MW & 2,219MW (Ramírez et al., 2020). The North-sea and Baltic sea have consistent strong wind and shallow waters, making them the most popular offshore wind farm deployment site.

In the past decades, offshore wind development has been limited to shallow waters with a depth of less than 60meters, where only a fixed button foundation can be installed. The future of offshore wind is moving to deeper waters where the water level is greater than 60meters, thus paving the way for floating foundations. Factors influencing the deployment of floating wind turbines include the saturation of nearshore offshore sites, immense wind resources, and the high demand for operational rated capacity (IRENA, 2019; Ramírez et al., 2020). The Hywind Scotland is the world's first floating turbine with five 6GW Siemens direct-drive turbines and a total capacity of 30MW. It is situated in the north-sea, at a water depth between 95m – 120m, and operated by Equinor in a joint venture with Masdar (Equinor, 2019; Staoil, 2015). Equinor is currently developing the largest floating wind farm Hywind Tampen which consists of 11 Siemens Gamesa SG 8.0-167 direct-drive turbine with a total capacity of 88MW and is expected to be commissioned by 2022 (Equinor, 2021).

Although 80% of the total potential of offshore wind energy is located further away from the shore, the Fixed-Bottom turbine is still dominant in the European market (Estate, 2019) due to its cost-efficiency and its ability to offer reliable grid connectivity. The Monopile fixed-bottom foundation is the most adopted technology and was used to develop the world's largest offshore wind farm; The "Hornsea One project," sited 120km off the coast of Yorkshire, England, where water depth is between 20meters - 40meters. It has a 174 number Siemens 7MW wind Turbine with a total capacity of 1,218MW (Estate, 2019; Ramírez et al., 2020). Siemens Gamesa remains the Leading manufacturer of wind turbines and has a 63% market share from 1995 -2018 (IEA, 2019). In Europe, Siemens Gamesa turbines have a total installed capacity of 68.1% by the end of 2019 (Ramírez et al., 2020) and are more adopted by UK offshore wind farms, i.e., 8074MW of 10045MW and among the 8074MW turbines, 3754MW are direct drive.

1.1.1. Challenges and Prospects of the offshore wind system

The maintenance of offshore wind turbines is one major critical issue associated with offshore wind, and the cost is estimated to be between 20% - 30% of the Levelized cost of energy (LCOE)(Dewan & Asgarpour, 2016). These costs can be reduced by optimizing operation & maintenance strategy. Although offshore wind O&M is similar to onshore activities, there are notable exceptions such as exposure to high wave height, tide, and harsh weather, especially during winter, which poses challenges and risk relating to work and accessibility of offshore wind farm (Gebruers, 2015; Van Bussel et al., 2001). Offshore wind farm O&M is a complicated and expensive task mainly influenced by the wind farm size, shore distance, site exposure, and the maintenance strategy involved. The maintenance strategy selection is dependent on the farm location. For instance, the North-sea is group into three regions based on the water depth, southern bright (<40m), central north-sea (40m-100m), and northern north-sea (100m-200m) (Paramor et al., 2009). Wind farms' most popular access strategy is the crew transfer vessel (CVT), but it operates only at a wave height of 1.5m and calm waters. Alternatively, modern offshore projects are featuring Helideck or Heli-hoist platforms to improve direct access to the turbine at critical times. The Horns Rev in Denmark and Alpha Ventus currently use Helicopters in regular turbine O&M. Service offshore Vessel (SOV), and offshore base O&M concept is considered for large wind farms further away from shore (>50km). They host spare parts, repair facilities, and technicians for a longer period offshore for faster and efficient maintenance tasks (Dewan & Asgarpour, 2016). These access strategies have drawbacks, it is either affected by extreme weather condition or high cost.

The Maintenance activities for offshore wind include corrective and preventive maintenance. The experience gathered from Tunø Knob wind farm(Van Bussel et al., 2001) shows an annual service visit of 35 to 75 visits, approximately 5 services per year for each turbine. Similarly, the report from SPARTA (System performance, availability and reliability trend analysis) also shows an average of 6 visits per year for UK windfarms and having a greater number of transfers for the turbine in the less harsh summer months, i.e., April – August (SPARTA, 2018). On average, offshore wind farms experience ten failures per turbine per year, where 80% are minor repairs, major repairs, and major replacements are 17.5% and 2.5%, respectively (Carroll et al., 2016). The preventive maintenance is scheduled, which is normally twice per year or condition-based, where maintenance is done depending on the health of the component. "*The actual availability of offshore wind turbines is a function of machine properties, location accessibility, and maintenance method"* (Van Bussel et al., 2001). Maintenance activities are the leading cause of turbine downtimes, and currently, the availability of offshore wind turbine systems is between 80% to 90% (Hassan, 2013).

The demand for O&M is considered a key aspect in the development phase. Project operators are turning to a smarter maintenance strategy to boost maintainability and increase availability. One such technology is the digital twins of the physical turbines, which enables real-time monitoring of the project and maintenance planning. Another study, according to (Jonker, 2017) suggests a predictive approach using smart sensing systems to monitor critical components of the turbine and collect data that can enhance the performance of the offshore wind turbine. Other technologies like autonomous drones can be used for blade inspections (Deign, 2016) and ROV for inspecting the foundation (Mathiesen et al., 2016). However, this research is dedicated to developing the maintenance concept for offshore wind turbines and illustrating how the Smart maintenance concept can be applied to optimize the maintenance operation.

1.2. Research objectives and relevance

This research aims to create a baseline maintenance concept and develop a Smart maintenance concept (user case scenario) to improve the operation and maintenance of the offshore wind turbine system.

The relevance of this project is to help:

- Familiarize with the maintenance activities in the offshore wind industry
- Understand the steps involved in developing a maintenance concept for industrial asset
- Provide new knowledge regarding the applicability of the Norsok-Z-008 standard for the offshore wind industry
- To demonstrate the benefit of the applying Smart maintenance concept for wind turbine maintenance activities

1.3. Research question

Maintenance is one big challenge in the offshore wind industry. Both maintenance and reliability are the key drivers of the overall cost of energy. A good combination of technologies and maintenance strategies would provide the basis for a more intelligent maintenance approach that can improve the availability of the offshore wind system. Some academic researchers have identified different smart maintenance technologies (Christensen, 2018a). Still, there is a need to determine how they can be applied and to estimate the impact on the offshore wind system. It is quite easier to benefit from modern technologies such as autonomous solutions, cloud computing, mobile solution, and big data application in this era. However, the issue is to know how and where to begin.

The main research question therefore is:

How can Smart maintenance concept be applied to improve the maintenance of critical equipment in an offshore wind turbine?

Several steps have been adopted to ensure that all aspects are appropriately considered to answer this question. These steps are in accordance with the Risk-based maintenance approach, which is already given in the Norsok-Z-008 standard for Oil & gas sector. However, the methodology is providing new original knowledge for offshore wind power applications. The procedures are explained briefly in section 1.4**.** Chapter 2 also illustrates the design philosophy, data source, and output of each step taken to answer the research question.

1.4. Methodology

As mentioned previously, the adopted methodology step is based on the risk-based maintenance approach (NORSOK-Z-008). However, an investigation into the current practices in the wind sector was carried out using books, online journals, and reports to present a detailed insight into the offshore wind industry, the maintenance challenges, and prospective turbine design technology. The Technical Hierarchy for the offshore wind turbine was developed to get an overview of how the system is technically built and the connection between components. The technical hierarchy was done using the ISO 14224 standard. The NORSOK Z-008 standard was used to develop the functional hierarchy and consequence classification for the equipment listed in the technical hierarchy. The Failure mode and effect analysis (FMECA) was developed for the component that scores high or medium critical level in the consequence classification. The FMEA aims to identify the dominant failure mode and root cause to justify the equipment to focus on. An effort was made to explore the maintenance activities for offshore wind turbines (i.e., typical task, frequency). This was achieved through a literature review and by consulting the wind farm site manager and operator, and original equipment manufacturers (OEM). This information was reviewed and used to set up a baseline maintenance concept illustrating the maintenance activities for each failure mode identified in the FMEA. The conceptual baseline was used as the first step to develop a smart maintenance decision workflow showing how to improve maintenance base on three use case scenarios.

In summary, this thesis consists of the following activities:

- First is a literature study to get an overview of the offshore wind power sector and the operation & maintenance activities and critical challenges
- Develop Technical Hierarchy for the offshore wind turbine (based on ISO 14224)
- Develop Functional Hierarchy and consequence classification (based on NORSOK-Z-008)
- Develop FMECA for the offshore wind turbine and justify the focus component
- Get an overview of the planned maintenance campaign, i.e., identification and development of activities in maintenance and test concept, including intervals for preventive maintenance and taking smart maintenance, CBM, etc. into consideration
- Develop a smart maintenance concept to improve the maintenance operation
- Discuss the result from the implementation of the smart maintenance concept

1.5. Scope of the thesis

The scope of the thesis is limited to illustrating how smart maintenance can be applied to only the critical equipment of the offshore wind turbine system. The system selected is the Direct-drive wind turbine with a fixed-bottom Monopile foundation.

1.5.1. Limitation

However, this thesis is limited to:

- RBM and smart maintenance for offshore wind turbines
- The focus was only one wind turbine system and the most critical equipment in the turbine
- The wind turbine structural support system and balance of plant (Tower and Foundation, cable) are not covered in this report.
- Only one use case scenario was implemented to demonstrate the benefit of using the Smart maintenance concept

1.6. The structure of the thesis

Chapter 2:
This section presents the research design to answer the main research question and the objective of this thesis. The proposed research design illustrates all the steps that would be taken throughout the research. The research philosophy, approach, method, data sources, methods of collection, and analysis are also discussed.

Chapter 3:
This chapter presents a comprehensive literature review of different relevant topics. It consists of theories about the application, theories about the topic, and theories about the method adopted in this research.

Chapter 4:
This chapter is the Data collection chapter. It contains the case description and the processes involved in collecting data from different sources. The data source for each step of the methodology is described in detail. The questions for the interview conducted are also presented.

Chapter 5:
This chapter comprises the analysis carried out to achieve the goal of the thesis. It also presents the results of each step. The steps adopted is the same steps presented in the research methodology

Chapter 6:
This chapter consists of relevant discussions and limitations of each step taken in the analysis chapter 5. A general recommendation for further research work is also presented at the end of the chapter.

Chapter 7:
This chapter presents a summary of this research. It comprises the main conclusion regarding the formulated research question and subsequent conclusions drawn from each step taken to answer the research question. It also presents a general contribution of this research

Chapter 2

2. Research methodology and design

This chapter presents the research design that was established to answer the main research question and the objective of this thesis. The proposed research design illustrates all the steps that would be taken throughout the research. The research philosophy, method, data sources, methods of collection, and analysis are also discussed.

2.1. Research Design and Philosophy

This research aims to create a maintenance concept for offshore wind turbines and develop a Smart maintenance concept (use case scenarios) to improve the maintenance operation for the critical component of the offshore wind turbine system. Therefore, this research is interested in exploring how applicable is smart technologies in the maintenance of offshore wind turbines.

In scientific work, the belief of how information is obtained, analyzed, and implemented is expressed by the research philosophy. There are different philosophical worldviews, such as positivism, interpretivism, pragmatism, critical realism, and constructivism (Creswell, 2014). The proposed steps in the methodology to answer the research question requires multiple research philosophy. Table 1 shows the different philosophies applied to each step in the methodology, and a brief description follows.

Table 1. Research methodology step and philosophy

	Steps	**What is the Core activity**	**Philosophical view**
1	System description	Describe the system and how it operates to get a good understanding	Critical realism,
2	Technical hierarchy of the selected wind turbine design	Identifying and groping of wind turbine equipment and component according to their location	Critical realism, Constructivism
3	Functional hierarchy and consequence classification	Identify the functions and subfunctions of the systems and component	Pragmatism, Constructivism
4	Failure mode and effect analysis (FMEA)	Identify the root cause of failure, rate the severity, occurrence, and frequency	Pragmatism, Constructivism
5	Manning study/ Baseline maintenance concept	Construct the maintenance concept representing the real-world case	Interpretivism, Constructivism
6	Smart maintenance study	Develop a smart maintenance flowchart using use case scenarios. simulating	Constructivism, Postivism
7	Comparison study	Compare the result from step 6 to illustrate the benefit	Interpretivism,

- The Philosophy adopted in the first step is critical realism. The step depended on a comprehensive literature review to identify and understand the operational mechanism of the wind turbine
- The second step will apply constructivism research philosophy to develop the technical hierarchy of the wind turbine system. Furthermore, critical realism can be added because the hierarchy development is also based on background knowledge from relevant literature reviews.
- The research philosophy to be applied in the third step is both pragmatism and constructivism. Constructivism will be applied to create the system's functional hierarchy based on the result

from the second step. However, several inputs and criteria were explored to define the critical function of the selected wind turbine, which makes it also pragmatic

- In the fourth step, the critical failure function from the previous step shall be explored by carrying out a failure mode and effect analysis. This involves using historical failure data, identifying the root cause of the failure, and rating the severity, occurrence, and detection parameters. Therefore, the pragmatism research philosophy is applied
- The fifth step applied interpretivism to extract maintenance information from stakeholders relating to the failure modes specified in the fourth step. Base on the information obtained, constructivism research philosophy shall be applied to develop a conceptual maintenance model for the critical failure mode wind turbine equipment
- Sixth, constructivism research philosophy was applied to develop a smart maintenance model and the use case scenarios associated with optimizing the maintenance concept developed in step 5. The flowchart developed will be verified by implementing one scenario and validated through expert judgment
- The last step applied interpretivism research philosophy because it has to do with comparing the result from step 5 and 6

The approach used in this thesis is a combination of both the Inductive and Deductive approaches. The research is Deductive because it involves developing and simulating the maintenance operation for offshore wind turbines based on already established knowledge about maintenance activities. The research is Inductive because it involves developing a smart maintenance concept for optimizing maintenance operation in offshore wind turbines. However, a combination of both approaches makes it an "*Abductive research approach*."

The strategy applied is both case study and simulation modeling method based on the philosophy and research approach. The case study comprises a comprehensive literature review about the topic and developing a baseline maintenance concept and a smart maintenance concept. The simulation modeling study involves simulating both the maintenance timeline for both concept using Anylogic software

2.2. Research Methods and Techniques

The steps adopted to answer the research question are presented in table 2. It also consists of the data source, data collection method, analysis method, and the validation action taken for each step.

Table 2. The research methodology and design

Steps		Data source	Data collection	Analysis	Reliability and Validity actions
1	System description	Literature review journals and report relating to the wind turbine (IRENA, IEA)	Literature review, Focus group	Icam DEFinition for Function Modeling (IDEF diagram)	Online literature, study group, Expect opinion
2	Technical hierarchy of the selected Turbine design	Online Literature review, Relia wind taxonomy	Literature review, Focus group	Microsoft Excel worksheet, ISO 14224	Checking traceability with ISO 14224 standard, Expert opinion
3	Functional Hierarchy and consequence classification	Literature review, NORSOK Z-008 standard, Risk matrix, Risk decision criteria	Literature review, Focus group	NORSOK Z-008 standard, Risk decision criteria, Microsoft Excel worksheet	Expert opinion, study group

4	Failure mode and effect analysis (FMEA)	Literature review. ISO 14224 Standard, FMEA Rating scale,	Literature review, focus group	FMEA, Microsoft Excel worksheet, Risk decision criteria, ISO 14224,	Expert opinion, study group
5	Manning study	Literature review, SPARTA database, interview with operator and OEM	Interviews with stakeholders	Manning study, Microsoft Excel worksheet, Anylogic	Experts opinion, study group
6	Smart maintenance study	Expert perception about smart maintenance, Literature review	Focus group	Flow chart, Microsoft Excel worksheet, Anylogic	Expert opinion,
7	Comparison study	Simulation result from step 5 and 6	Simulation results from step 5 and 6	Comparison analysis	Expert opinion, study group

Step 1: This phase involves the system description. I have built the operating case of the direct-drive turbine. The main data source for this step is online literature related to offshore wind turbine development; therefore, secondary data collection methods will be utilized.

Step 2: I plan to develop the Technical Hierarchy for the direct-drive wind turbine system. The levels and terminology adopted will be based on the ISO 142224 standard, where the plant, system, equipment unit, and maintainable component will be defined. I have utilized the Microsoft Excel worksheet for this analysis. Experts verified the technical hierarchy from the case company and through comparison with related standard and taxonomy literature.

Step 3: Base on the technical hierarchy developed in step 2. I shall build the functional hierarchy and consequence classification of the selected system. The functional hierarchy will identify the main function and sub-function of the equipment specified in the technical hierarchy. I adopted the NORSOK Z-008 guidelines to establish the system's functional hierarchy, and the case company provided the risk criteria. I have utilized the Microsoft Excel worksheet for this analysis. The functional hierarchy will be verified based on relevant literature and expert opinion

Step 4: Based on step 2, I carry out the Failure mode and effect analysis (FMEA) for the component with high and medium criticality scores in the consequence classification. I adopted the failure mode description style in ISO 14224. This step depended on the failure dataset from relevant literature.

Step 5: I have conducted a semi-structured interview with operators and wind farm site managers to get an overview of the maintenance activities for an offshore wind turbine. This will enable me to develop a maintenance concept using a Microsoft Excel worksheet and simulated it using Anylogic software to visualize the maintenance event for each wind turbine equipment.

Step 6: To improve the maintenance operation for the wind turbine, I have developed a smart maintenance flowchart illustrating the associated use case scenario. The use cases adopted were based on an ongoing study in the case company (Aker solution). The flow chart will be implemented to show the added value. I have used Anylogic software to simulated the new maintenance event. The flowchart was verified by my supervisors and other expert opinions

Step 7: In this step, I have discussed and compared the results from steps 5 and 6. It involves demonstrating the improvements from implementing the smart maintenance flowchart developed in step 6.

Chapter 3

3. Theoretical background

This section presents a comprehensive literature review of different relevant theories. It consists of three theory phases. The first provided a more detailed general theory about the offshore wind industry which discussed offshore wind turbine infrastructures, failure components, the operation & maintenance activities, and challenges. The second theory phase is related to the topic. It discussed Smart maintenance operation and technology trends. The third theory phase is about the applied methods, which discussed risk-based maintenance approach, turbine technical hierarchy, FMEA, maintenance task selection, and modeling &simulation. The EndNote software was used for reference management

3.1 Offshore Wind Energy Status and outlook

Since the start of the 21st century, the global wind industry has witnessed significant growth and is the fastest-growing renewable technology. In 2019, the offshore wind energy market size exceeded $24 billion, and the compound annual growth rate (CAGR) is anticipated to grow increase by 14.8% between 2020 and 2026. (Gupta & Bais, 2020). Between 2010 and 2018, it grew almost 30% per year following the rapid improvements in technology, and about 150 new projects in offshore wind are currently in development globally (IEA, 2019). Europe is in the lead for offshore wind technology. As illustrated in Figure 2, the cumulative capacity of offshore wind power in Europe is about 22.5MW at the end of 2019 (Ramírez et al., 2020), with the United Kingdom having the highest operational offshore wind capacity followed by Germany. Although Denmark was the first country to install an operational offshore wind two decades ago, currently, offshore wind contributes 15% of Denmark's electricity in 2018 (IEA, 2019). Policy supporting offshore wind set to robust the growth of offshore wind energy in Europe four times more in the next ten years.

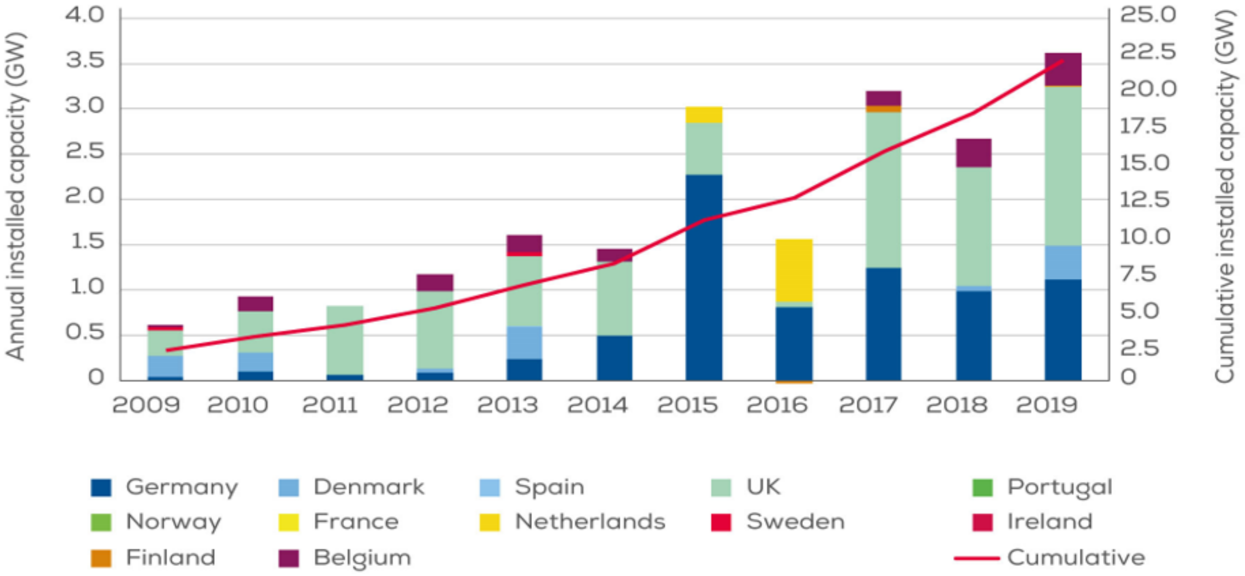


Figure 2. Annual Offshore wind installations in Europe from 2009 – 2019 (Ramírez et al., 2020) WindEurope

Table 3 below shows the 2019 overview of the total offshore wind power project for the top five leading European countries. The UK leads with a 9.9MW cumulative capacity and has 2,225 number of installed wind turbines. Both UK and Germany set a national record of installation in

2019 with 1760MW and 1,111MW representing 48% and 30% of the net capacity connected in 2019, while Denmark and Belgium amounted to 10%, respectively.

Table 3. Overview of 2019 grid-connected offshore wind power for Top 5 leading European Countries (Ramírez et al., 2020) WindEurope

Country	Number of Wind Farms Connected	Total Capacity (MW)	Number of Turbines Connected	Net Capacity Connected in 2019 (MW)	Number of Turbines connected in 2109
United Kingdom	40	9,945	2,225	1,760	252
Germany	28	7,445	1,469	1,111	160
Denmark	14	1,703	559	374	45
Belgium	8	1556	318	370	44
Netherland	6	1,118	365	0	0

3.1.1 Main stakeholders

As illustrated in Figure 3, the O&M provision for the offshore wind farm is driven by three major stakeholders: project owners, wind turbine original equipment manufacturer (OEM), and offshore transmission owner (OFTO) (Hassan, 2013). It is the responsibility of the Project owner to procured the offshore wind operational services. They are also involved in selecting the operation strategy and can transfer the responsibility to the OEM. Depending on the contract, the OEM is in charge of the maintenance, logistics, and onshore infrastructure, while the OFTO is responsible for the offshore transmission structure (Hassan, 2013).

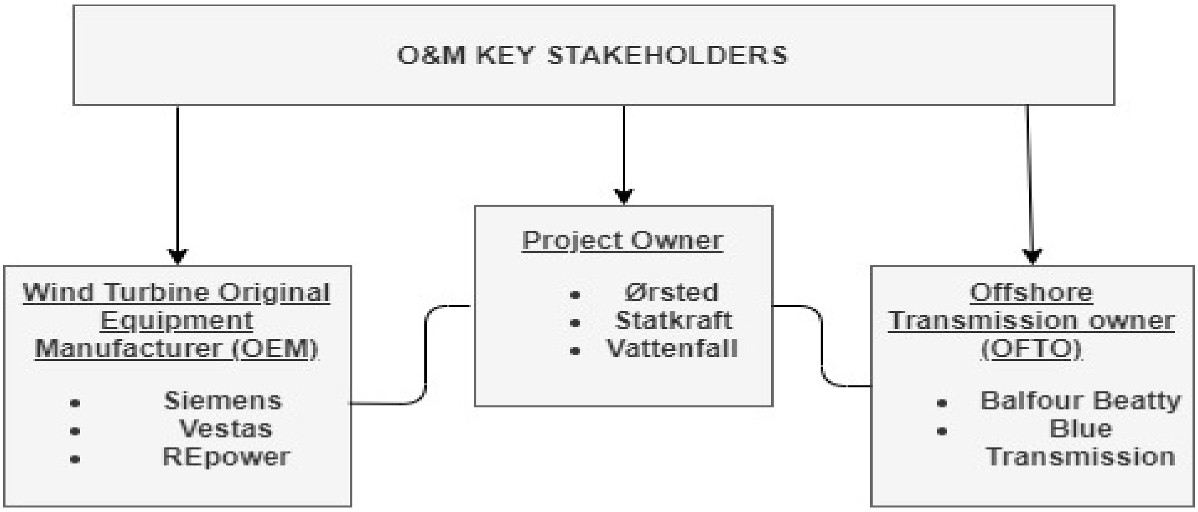


Figure 3. O&M key stakeholders (Hassan, 2013)

3.1.2. Offshore Windfarm selection

One crucial decision to make during the offshore wind turbine system development is the Selection of the Farm site. There are some factors that have to be considered before selecting the site for your wind farm, and a proper approach is required to ensure that all relevant site information a well gathered. Some literature has provided some criteria and techniques for the Selection of offshore wind locations. See Ref. (Van Haaren & Fthenakis, 2011) & (Lee et al., 2010). These criteria are based on social, economic, and environmental factors. Some important considerations are the wind resources, the farm size & the intended turbine capacity, seabed condition, the depth of the water, the distance to shore, the O&M cost, as well as the government policy (Deveci et al., 2020). The most popular site of offshore wind deployment is the North sea due to the consistent strong wind and shallow waters it provides (Musial & Butterfield, 2004). About 77% of the cumulative installed offshore wind farms are in the North-sea, making up 16,908MW (Ramírez et al., 2020). The North Sea has about 750,000 square kilometers and is grouped into three regions based on the water depth. The southern bright (<40m), central north-sea (40m-100m), and northern north-sea (100m-200m) (Paramor et al., 2009). Figure 4 below illustrates the mean wind speed at different regions of the North Sea for each season. From the color scale, notice that winter and autumn season has the strongest wind than the rest seasons.

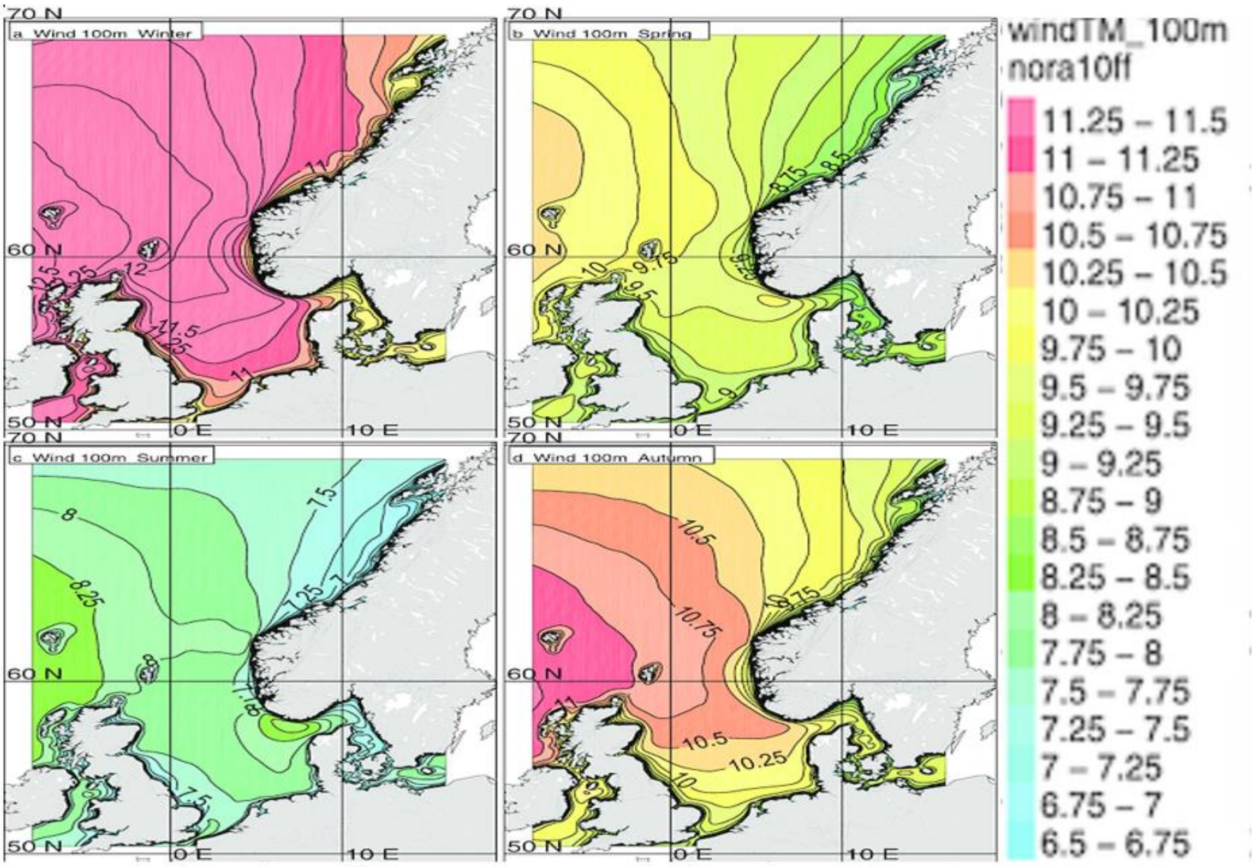


Figure 4. Map of the mean speed for each season in the North sea. (Furevik & Haakenstad, 2012)

(Source: Journal of Geophysical Research: Atmospheres, Volume: 117, Issue: D23, First published: 07 December 2012, DOI: (10.1029/2012JD018523))

3.2. Offshore Wind Turbine and Infrastructures

As presented in Figure 5, the main components in an offshore wind turbine include the Blade, Hub, Nacelle, Tower, and the Foundation. The wind farm located offshore consists of several wind turbines depending on the designed total capacity. The total power generated is linked to a collection system and the offshore substation by submarine power cable before it is transmitted to the onshore power station (Dedecca et al., 2016). Wind farms mostly adopt the High voltage alternating current (HVAC) power transmission systems. It is made up of a power circuit, reactive power compensation equipment, offshore booster station, and submarine cables. The HVAC converts the power collected to Direct current to reduce transmission losses; then, it will be transported to the onshore station where the power is converted back to Alternating current before feeding it to the grid network (CNBM, 2017). For example, in some cases, the Hywind Tampen offshore wind farm, the power generated is not transmitted onshore; rather, it is used to power the Gullfaks and Snore oil & gas fields in the Norwegian north-sea (Equinor, 2021).

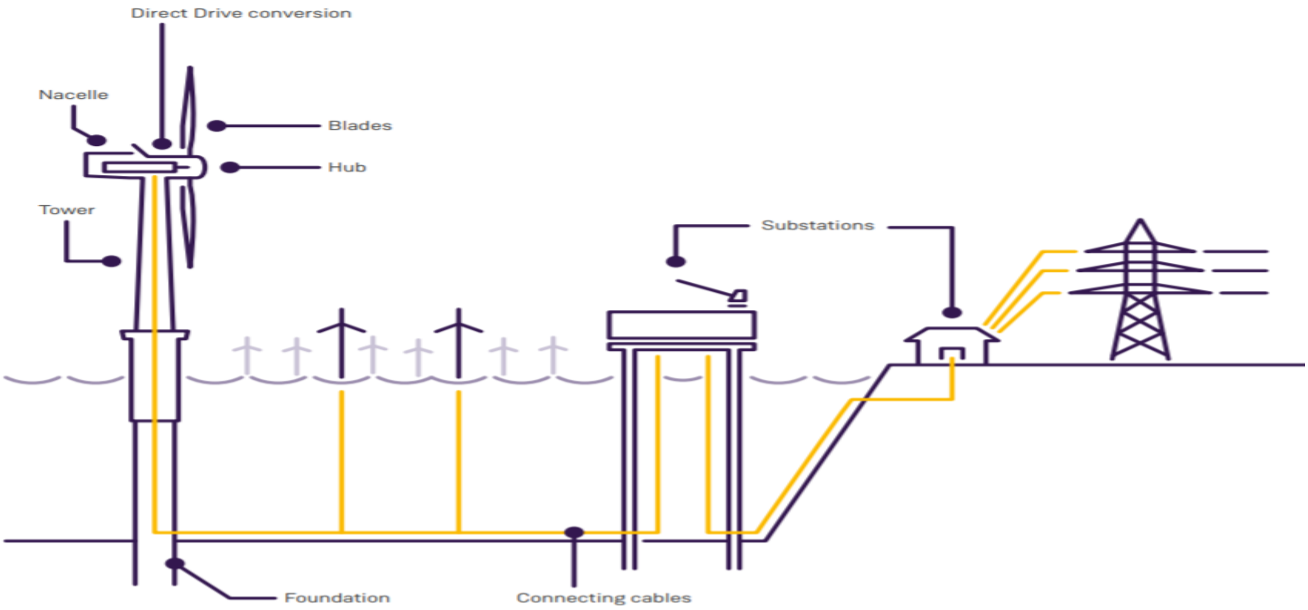


Figure 5. Offshore wind turbine main components and transmission system (Siemens-Gamesa, 2021)

3.2.1 Offshore Wind Turbine Foundation Design

The foundation choice for an offshore wind turbine is dependent on the water depth, site environment condition, and seabed condition. About 25 to 34% of the offshore wind turbine development cost is attributed to the foundation cost, which implies that energy cost could experience a significant decrease if there is a reduction in the cost for support structure (Bhattacharya, 2014). The two kinds of offshore turbine foundations available include the Fixed-Bottom foundation and the Floating Foundation.

3.2.1.1. Fixed-Bottom Foundation

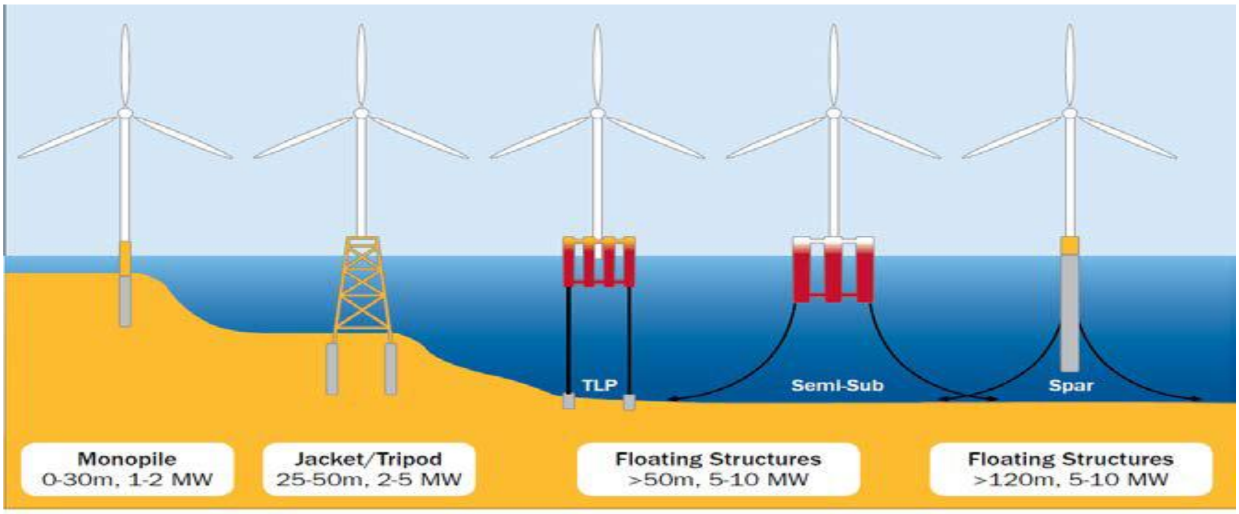
Most offshore wind turbines fully commissioned and operating in the world today have fixed-bottom foundation types. This foundation technology is installed at a water depth between 0- 60 meters. It has been well-adopted over the past decades due to its ability to deliver energy with a high-capacity utilization factor (CUF) (Gupta & Bais, 2020). It also offers reliable grid connectivity and is economical. Some known examples of fixed foundation design are shown in Figure 6 in and are briefly stated in Table 4

Table 4. Major types of Fixed-Bottom offshore wind turbine foundation

Foundation Type	WATER DEPTH (Meters)	STRUCTURE	GROUND
Monopile	Between 15m – 25m	Thick steel cylinder driven about 30meter depth	Sandy- clayey
Gravity	Less than or equals 30m	Concrete or Steel platform of about 15meters in diameter	Requires initial terrain preparation
Jacket	Over 30m	Steel-beam structure have a 3/4 anchor point with a length over 60 meters	Different non-rocky soil type

The monopiles foundation is the most adopted offshore wind turbine foundation. The deployment of monopile foundation technology at a water depth of less than 30meter requires less research and development effort (Musial & Butterfield, 2004). The Monopile foundation technology was used to develop the world's largest offshore wind farm; The "Hornsea One project" sited 120km off the coast of Yorkshire, England, where water depth is between 20meters - 40meters. It has 174 wind turbines with a total capacity of 1,218MW.

However, the Bottom-Fixed foundation, limited to a water depth of less than 60meter, is a major drawback. Therefore, more opportunities and new markets will arise if the offshore wind is freed from fixed-bottom designs. For example, a potential large offshore market like the US and Japan has less availability of shallow water; therefore, a Floating foundation design would be a better choice in such situations (IRENA, 2019).



Source: Principle Power

Figure 6. Offshore wind turbine foundation technologies (Bailey et al., 2014)

3.2.1.2. Floating Foundation

As offshore wind tends to move further into deeper waters, Floating foundation technology becomes preferable and economical. The floating foundation technology is deployed in water depth from 60 meters and above. Factors influencing the deployment of floating wind turbine includes the saturation of nearshore offshore sites, immense wind resources and the demand of high operational rated capacity turbines (Selbyville, 2020). As the Turbine capacity increases, the further from shore, the wind farm must be located to harvest better wind resources. Floating foundation design has been described as a game-changing technology with abundant potential to exploit deeper water and significantly increase offshore wind power market growth (IRENA, 2019). The Spar-buoy floating design was used to develop the world's first floating offshore wind farm; The Hywind Scotland, commissioned in 2017, has five 6GW turbines and a total capacity of 30MW. It is situated in the north-sea, 25km off Peter-head, the UK, where water depth is between 95m – 120m. Equinor operates it in a joint venture with Masdar (Equinor, 2019; Staoil, 2015)

The potential of floating wind can notably favor large population markets like Japan and the US, where there is deep water. Asia would experience a significant increase in offshore wind power deployment in the coming years. For example, China has an offshore wind potential of over 1,127GW in water depth between 20m – 50m while at depth 50m – 100m, the potential increases to 2,237GW (IRENA, 2019). *Table 5* shows the offshore wind resources share and the potential for floating wind in some regions.

Table 5. Floating wind Potential in major economies(IRENA, 2019)

Country/ Region	**The shares of offshore wind resource having Floating Technology (Depth >60M**	**Potential for Floating wind (MW)**
Europe	80%	4,000
US	60%	2,450
JAPAN	80%	500

3.2.2. Wind Turbine Drive train

The nacelle housed several components of the drive train and is regarded as the powerhouse of the turbine. Significant progress into a new concept has been made towards the design modification of the turbine drive train. Mainly, development effort is focused on the

- Gear drive (gearbox)
- Direct drive

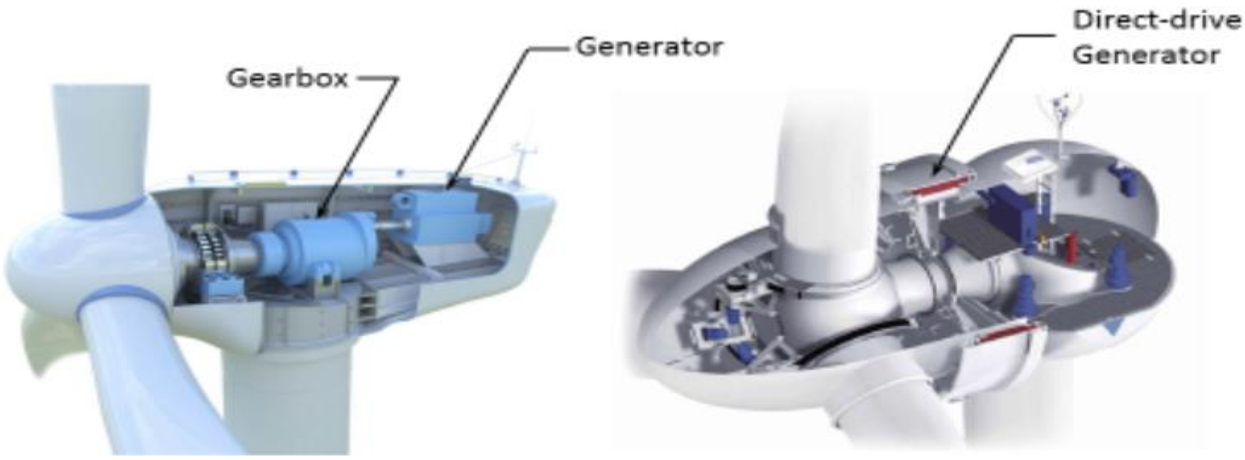


Figure 7. Turbine with gearbox (left) and turbine with direct drive (right) (Energy.gov, 2019)

In the typical conventional turbine, the gearbox is situated between the low-speed rotor shaft and the generator to increase the rotational speed from about 1000rpm to 1800rpm, required by the generator to produce electricity. On the other hand, the Direct drive eliminates the presence of a gearbox. The generator is directly coupled and power by the rotor. Although the rotational speed is low, the generator consists of several permanent magnets that enable the desired high output (Osmanbasic, 2020).

3.2.3. Comparison Between Gearbox and Direct drive Wind Turbine

The gearbox turbine has presented several challenges to designers due to its failure frequency. Over 26% of the turbine downtime can be attributed to gearbox failure. It is the highest maintenance component in the conventional turbines cost due to the many moving parts and often does not reach the projected 5years span (Friedrich & Lukas, 2017). Failure does not necessarily begin as gear failure; it mostly starts from moving parts like the bearing location, leading to the deterioration of the gear teeth due to bearing debris and surface wearing. Misalignment would arise as a result of excess clearance. Eliminating the use of a gearbox and adopting the direct drive model increase the reliability of the turbine because of fewer moving parts, which also reduces maintenance effort. The comparison of both drive trains was presented by Tavner et al. (2006), focusing on the overall reliability of the WT. The report stated that direct drive is less reliable than the gearbox. It pointed out that the direct drive has increased generator and electric system failure irrespective of the gearbox failure, which cancels out the potential increase in reliability (Tavner et al., 2006). Other experts recognized the overall availability of the turbine is higher with the direct drive model due to the meantime to repair (MTTR). The MTTR of the gearbox is greater than the MTTR for the electronics component in the Direct Drive (DD) (McMillan & Ault, 2010). Pérez et al.(2013) also compared both types of the drive train, stating that electrical and electronic component has a greater failure rate in the DD than the gear drive turbine. However, the gear drive failure causes more significant downtimes (Pérez et al., 2013).

Generally, more gearbox turbines are installed today, but the DD will dominate in the coming decade and is currently the most adopted model in the UK market. Another research by Carroll et al. (2017) analyzed four drive train configuration performance as shown in Figure 8, based on the availability and O&M cost. The result, as shown in Figure 9 concludes that the permanent magnet generator (PMG) DD is the configuration with the highest availability even when position further away from the shore. This is because of the reduced failure rate and MTTR of the DD configuration as compared to turbines with gearbox configurations. Also, an expensive jack-up vessel is not required during the maintenance of DD due to the absence of a gearbox; therefore, there is a reduction in the transport cost (Carroll et al., 2017).

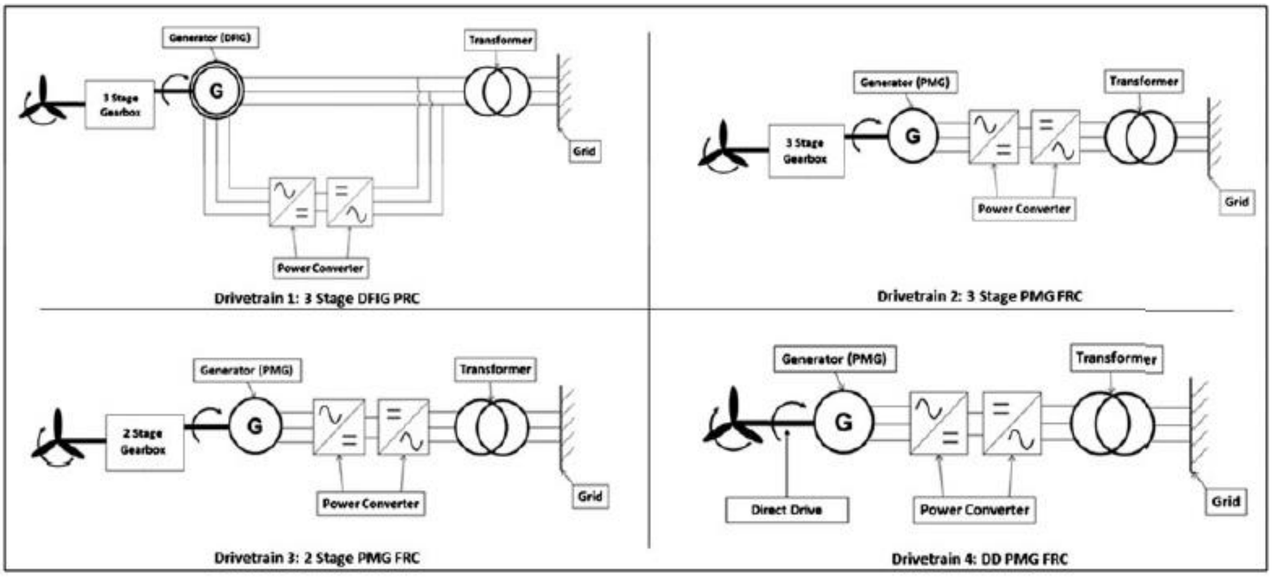
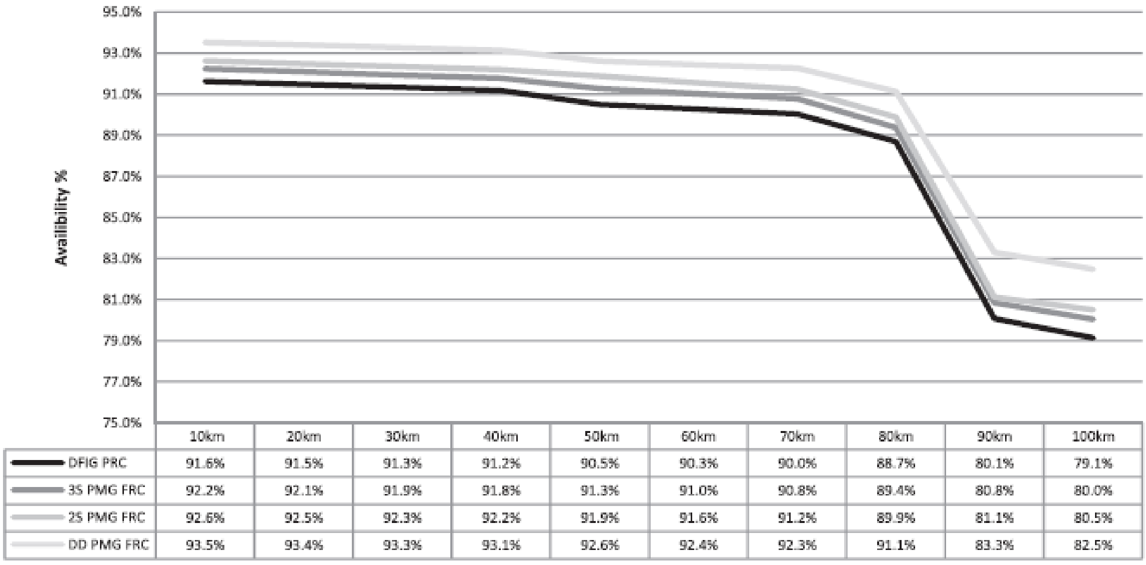


Figure 8. Drive train configurations for the wind turbine (Carroll et al., 2017)



	10km	20km	30km	40km	50km	60km	70km	80km	90km	100km
DFIG PRC	91.6%	91.5%	91.3%	91.2%	90.5%	90.3%	90.0%	88.7%	80.1%	79.1%
3S PMG FRC	92.2%	92.1%	91.9%	91.8%	91.3%	91.0%	90.8%	89.4%	80.8%	80.0%
2S PMG FRC	92.6%	92.5%	92.3%	92.2%	91.9%	91.6%	91.2%	89.9%	81.1%	80.5%
DD PMG FRC	93.5%	93.4%	93.3%	93.1%	92.6%	92.4%	92.3%	91.1%	83.3%	82.5%

Figure 9. Availability of drive train configurations at a different distance from shore (Carroll et al., 2017)

3.2.4. Power curve

The power curve of the turbine system represents the relationship between the wind speed and the generated output power, and it aids in monitoring the performance of the turbine (Sohoni et al., 2016). The power curve is usually given by the manufacturer and can be used to detect effects on the turbine's components, such as the generator. However, this is not always true, especially in offshore conditions due to external factors (Sohoni et al., 2016). The power captured (P) by the wind turbine is given by

$$P = \frac{1}{2}\rho\pi R^2 C_P(\boldsymbol{\lambda}, \beta)V^3$$

Siting a wind farm further away from shore brings about the wearing of turbine components is likely to occur. The direct-drive concept like the Siemen 6MW has fewer moving components, thereby decreasing failure likelihood. Siemens Gamesa direct-drive turbines are fitted with a “High wind ride through the system” (HWRT), which enables the stabilization of the power output (Jon Olson – Siemens, 2013). The power curve of the turbine is illustrated in Figure 10. A typical WT system shuts down at a wind speed greater than 25m/s to avoid overload, and the power production will be cut off. More stable power output is achieved even at higher wind speed with the aid of the HWRT system. It slowly limits the rotational speed by pitching the blade away from the wind immediately after the power output reaches its rated limit, thereby extending the operational duration. This advancement improves the grid network stability and reduces the WT component’s wearing caused by the turbine’s stoppage during high wind (Jon Olson – Siemens, 2013).

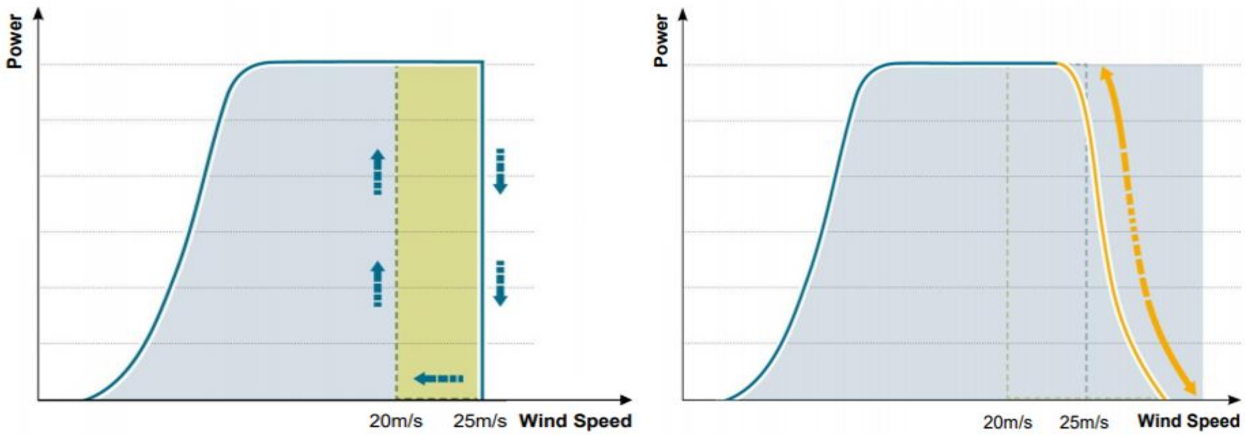


Figure 10. The power curve of the wind turbine, without HWRT, is to the left, with HWRT system to the right (Jon Olson – Siemens, 2013)

3.2.5. SCADA

Supervisory control and data acquisition (SCADA) is broadly applied in industries to aids monitor and controls the system. According to Tavner (2012), the status of the system is assessed by the SCADA system using sensors such as thermocouples, anemometers, and switches (Tavner, 2012). Data from the sensor are gathered and sent to the remote terminal unit, transmitting the data via the computer network, which analyses and displays the information. It processes and displays information about the system to aid in making relevant decisions (Automation, 2017). Every wind turbine is equipped with the SCADA system, and operators use it to monitor operational data and remote control of the offshore wind turbine. However, the data derived for the SCADA system typically depends on the manufacturer. Data are usually obtained every 10 to 15 minutes interval, and typical measurements are the weed speed, power output, wind direction, pitch angle, etc. (Mittelmeier et al., 2017).

3.2.6. availability

The wind turbine availability is described as the time at which the turbine can produce electricity divided by the total time in a particular period.

$$Availability = \frac{Time\ the\ turbine\ is\ able\ to\ operate\ in\ a\ given\ period}{Total\ time\ in\ that\ period}$$

(Carroll et al., 2016).

Some factors are influencing the availability of wind turbine systems, such as the failure frequency of the machine properties and the service demand. Also, external factors like weather conditions greatly influence the level of availability achieved. Figure 11 illustrates availability as a function of machine property, farm location accessibility, and the method of maintenance (Van Bussel & Zaaijer, 2001).

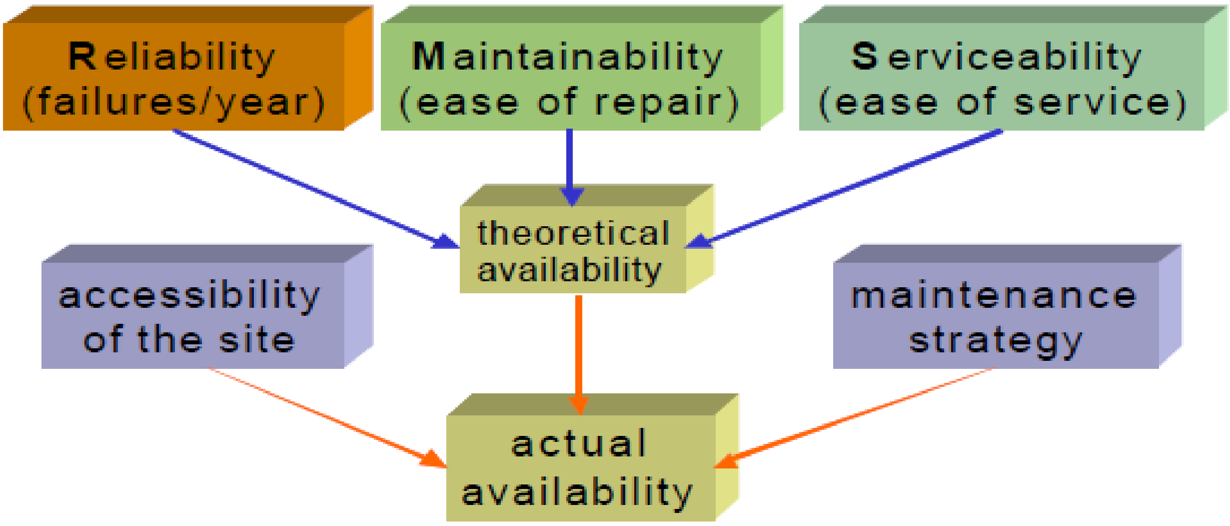


Figure 11. Theoretical and actual availability (Van Bussel et al., 2001)

The availability level for the onshore turbine system is relatively high, which is 98% and beyond sometimes. This is achieved through regular maintenance activities, which are quicker and performed in time. Maintenance visits for onshore wind turbines can be four times per year, either for planned service or for repair actions. In the offshore condition, the availability is affected majorly by the availability of experienced technicians, limited maintenance equipment, and limited access to the farm site due to weather conditions. Since accessing farm sites is inevitable, the focus is paramount to reducing the failure rate of offshore wind turbine system components during the design phase and operation (Van Bussel & Zaaijer, 2001).

3.3. Offshore Wind Turbine Operation and Maintenance

Offshore wind turbine operation and maintenance is one major critical issue associated with offshore wind, and the cost is estimated to be between 20% - 30% of the Levelized cost of energy (LCOE) (Dewan & Asgarpour, 2016). It is a key segment of the offshore wind turbine life cycle and should be appropriately managed to achieve optimal maintenance. The availability of offshore wind turbines is between 80% - 90% (Hassan, 2013) and is affected by downtimes due to maintenance activities. As a result, there is higher turbine service demand and requirement compared to onshore. The weather condition had been a significant hindrance to offshore wind turbine maintenance. Availability can reduce during the winter season when weather conditions worsen, triggering an emergency shutdown of the turbine to avoid component damage (Tavner, 2012). Therefore, major maintenance operations are carried out during the period of less wind. The offshore wind turbine O&M is still at the early stage compared to the offshore oil & gas sector. Hassan (2013) presented a general overview of offshore wind operation and maintenance activities, as illustrated in Figure 12. These can be categorized into seven activities: offshore & onshore logistics, Turbine maintenance, export cable, grid connection, array cables, foundation maintenance and back office, administration, and operations (Hassan, 2013).

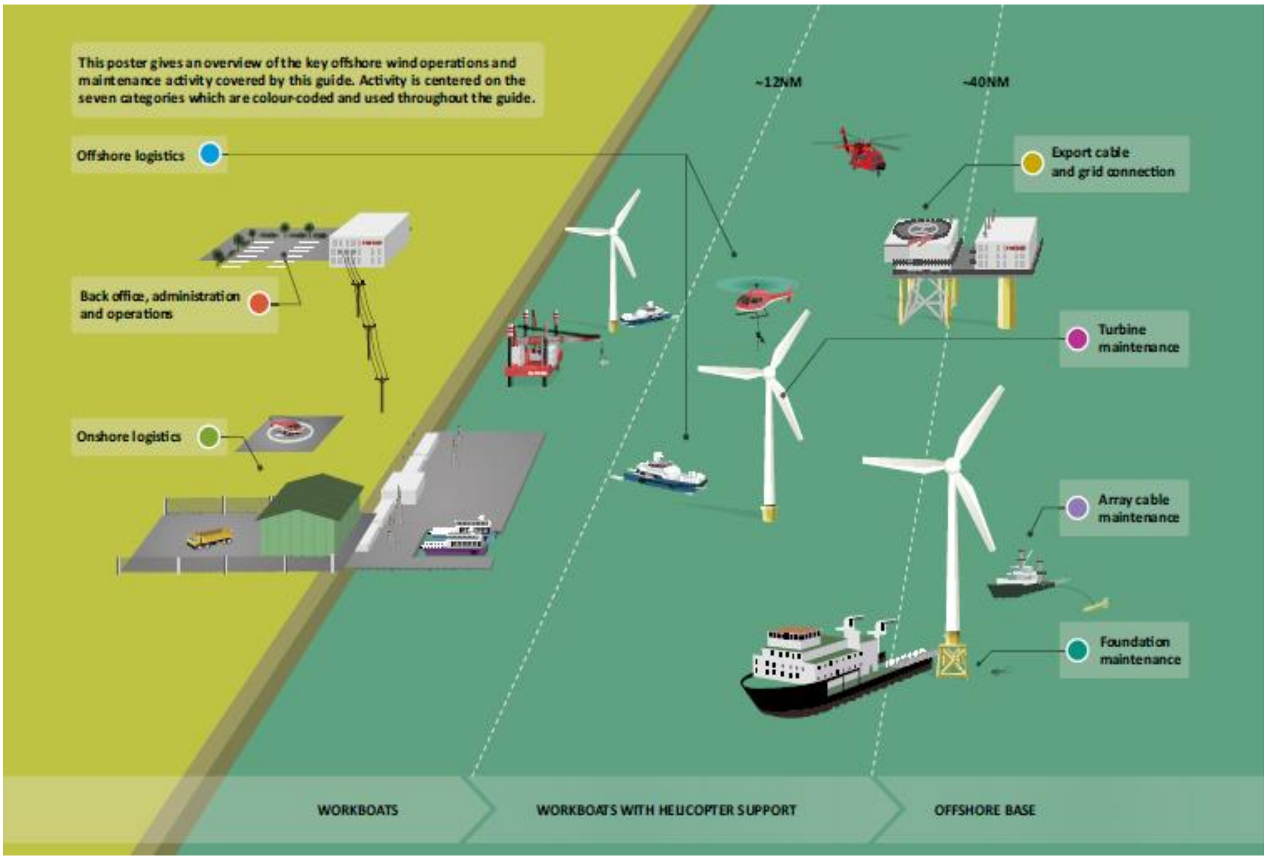


Figure 12. An overview of key O&M activities (Hassan, 2013)

3.3.1. Offshore Logistics and Accessibility

Logistics planning and access is another important aspect to be carefully considered during maintenance planning. It has huge implications on the cost of operation and maintenance and the overall availability of the offshore wind farm (OWF). Offshore logistics lies at the heart of O&M of OWF, and the primary aim is for the movement of technicians, types of equipment, and materials to be used for turbine repairs. Each offshore wind farm has different characteristics influencing the choice of maintenance strategies, such as the distance to shore facilities, average sea state, wind farm size, and the number of the turbine (Hassan, 2013). As shown in Figure 13, three main logistical strategies have been presented according to the report "*A Guide to UK Offshore Wind Operation and Maintenance*" by Gl Garrad Hassan (2013). This can be done by Workboat, also known as crew transfer vessels (CTV), Helicopters based and offshore-based mother vessels. Some projects may require a combination of those approaches depending on the farm characteristics. The different ways to access the wind turbine system includes

- Direct boat landing: Access to the platform is by climbing the ladder
- The platform: Provided direct access to the tower
- The helideck: it provides direct access to the nacelle

(Dewan & Asgarpour, 2016)

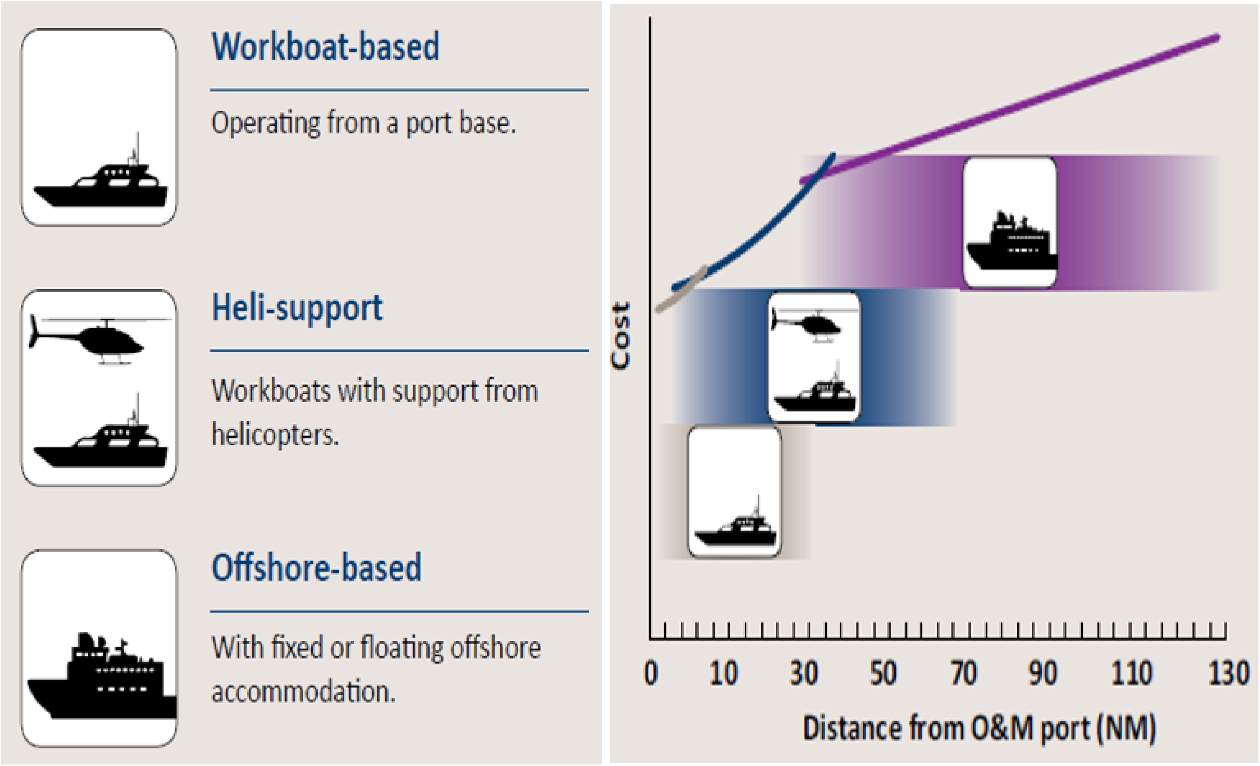


Figure 13. Strategic approaches to offshore logistics (Hassan, 2013)

The major contributor to turbine downtime can be attributed to accessibility restrictions. Harsh weather conditions do not only limit accessibility but also cause increased wearing of the turbine component. Hence, more service operation is required for achieving the desired reliability of components. Low visibility, high wind speed, and high wave height are the primary sources of access restriction. The offshore working period can be reduced by bad weather by up to 50% per month (Slengesol et al., 2010).

The crew transfer vessels (CTV) are commonly used for accessing the offshore wind farm site. The technician makes use of the ladder to access the wind turbine. CTV travel at high speed, cost-effective, and only suitable for wind farms located closer to shore. However, it does not accommodate many technicians and large spare parts and can be used at a maximum wave height of 1.5m (Dewan & Asgarpour, 2016). Alternatively, a helicopter base strategy can be used to support maintenance activities because it eliminates the Limitation caused by high wave height. Modern offshore projects are featuring Helideck or Heli-hoist platforms to improve direct access to the turbine at critical times. The Horns Rev in Denmark and Alpha Ventus currently use Helicopters in regular turbine O&M (Dewan & Asgarpour, 2016). However, poor visibility and high weed speed greater than 20m/s also limits the use of helicopter access strategy. It can be concluded that the CTV is more suitable for planned activities when there is no risk to the turbine, while the helicopter is suitable for unplanned activities when response time is critical to reducing turbine downtime (Hassan, 2013). Furthermore, the mother vessel is more suitable for a wind farm located further away from the shore. It hosts spare parts, repair facilities, and technicians for a longer period offshore for faster and efficient maintenance tasks.

A relative comparison of these strategies towards offshore wind O&M based on cost and distance to shore is also illustrated in Figure 13. Again, CTV or workboats is cost-efficient for nearby wind farms with helicopter support, while the offshore base or mother ship is cost-efficient for faraway from shore wind farms.

3.3.2 Turbine Maintenance

The maintenance of the WT system accounts for the highest share of the O&M effort. Maintenance activities are needed for adequate system performance and repair of the physical equipment in the system. The maintenance strategies can be categorized into corrective and preventive maintenance and shown in Figure 14.

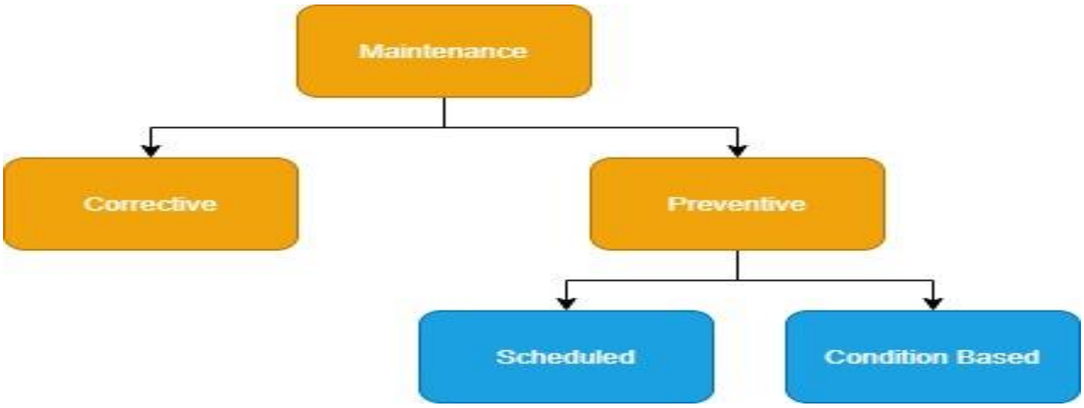


Figure 14. Maintenance types (Task, 2017)

Corrective Maintenance

For corrective maintenance, repairs or replacement for turbine components are carried out when a failure occurred. It can be a case of an emergency that requires immediate attention. However, this strategy can be expensive, especially in offshore situations where access is restricted by limited weather windows (Task, 2017). If corrective maintenance is to be implored, information about the failure rate and cost is required to estimate the cost of maintenance.

Preventive Maintenance

The preventive maintenance campaigns can be categorized into scheduled or condition-based, as illustrated in Figure 14. The scheduled maintenance is calendar-based, and the action is already predetermined. Knowledge about the expected lifespan and cost is needed if preventive maintenance is to be implored. For the condition base, maintenance activities are done based on information about the state of the component, deterioration rate, and cost obtained from the condition monitoring system (Task, 2017).

3.4. Wind turbine component and Failure rate and repair times

An offshore wind turbine's operation and maintenance practices are shifting from a costly corrective approach to more robust preventive and predictive strategies. It is crucial to understand how the WT component fails to develop a more cost-effective strategy. The severity of the failure, the rate of failure, causes of failure, repair time, and cost need to be well known, and this can be obtained from the manufacturer's maintenance logbooks or the failure database (Reder et al., 2016). However, there is also a need to categorize the WT component according to their physical system location and functionality to identify failure functions in each system. In (Jonker, 2017), the different Wind turbine component and their possible failures were specified. Also (Ribrant, 2006) categorized wind turbine components according to their function.

The degradation stages of wind turbine components are illustrated in Figure 15. The degradation process of WT drivetrain components (Le & Andrews, 2016) is based on condition monitoring methods. Each component in the WT begins at a stage of the normal working condition until the detection of excess vibration at T1. Moreover, T1 gives a pre-warning signal. After that, the component keeps degrading until it reaches T2, which is the critical condition where the component is exposed to excessive vibration and a rise in temperature. T3 is the failure stage of the component if no maintenance action is carried out (Le & Andrews, 2016). Different WT components must have individually defined critical stages because WT components have different critical characteristics such as current, temperature, and vibration. Condition monitoring may not be applicable for WT components such as the frequency converter due to its failure pattern, which can occur all of a sudden .i.e it goes from normal working condition to failure stage (Le & Andrews, 2016).

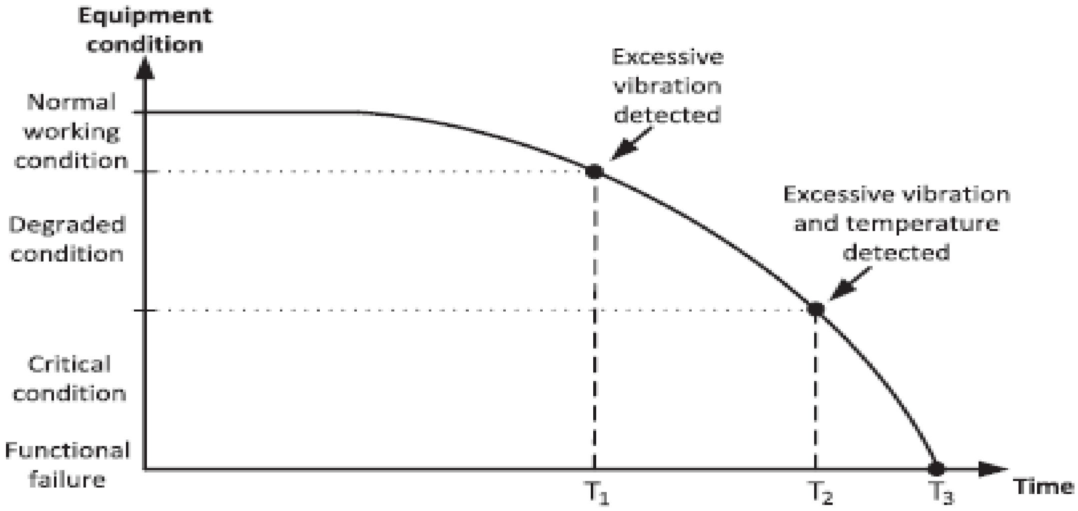


Figure 15. The degradation process of WT drivetrain components (Le & Andrews, 2016)

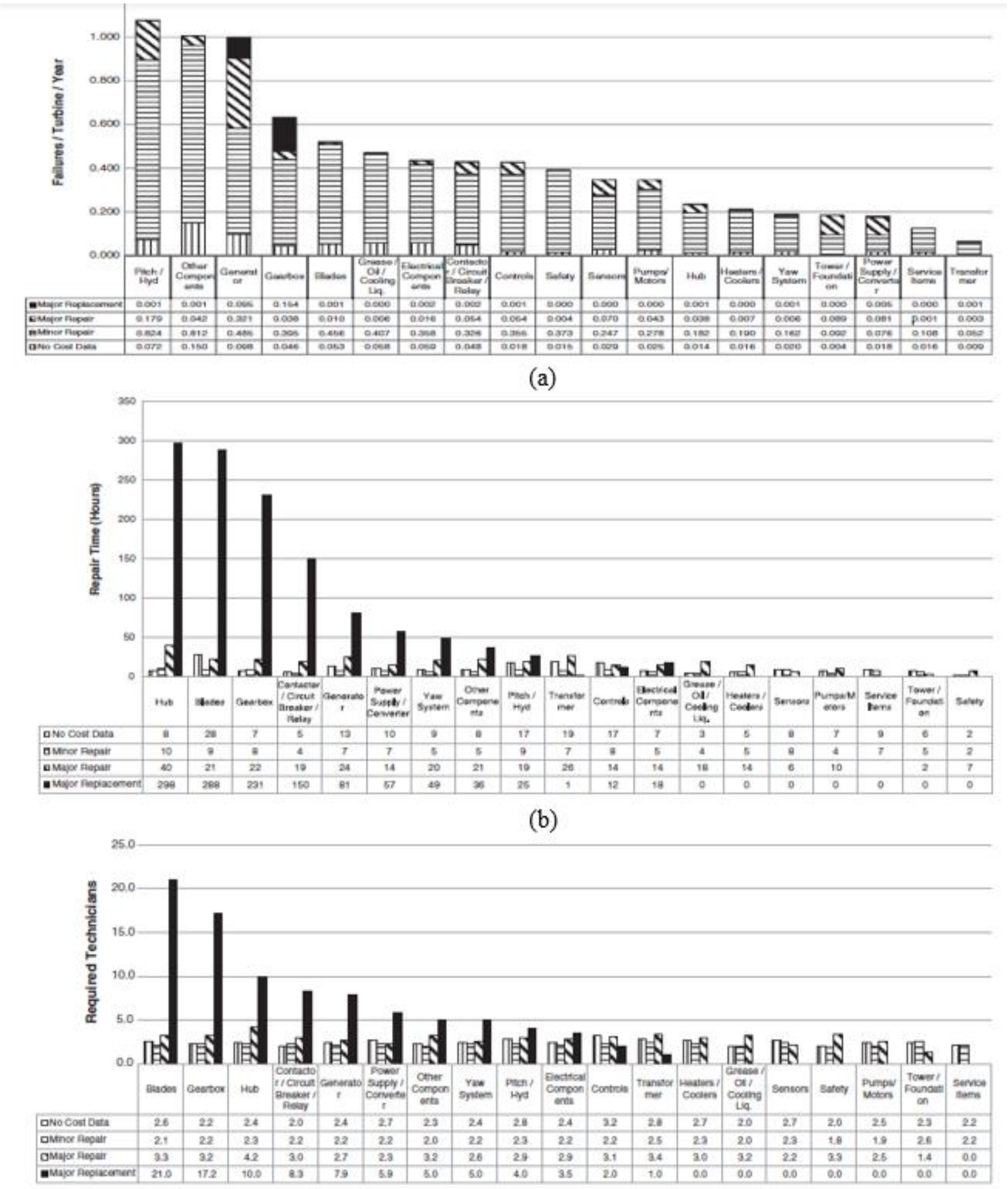
According to ISO 14224, failures are classified into three(3) stages

- Critical failure: Failure that can cause immediate loss of the ability of a component to perform the function required. It can be loss of ability to continue production or loss of ability to function on-demand, and immediate maintenance action is required.

- Degraded Failure: This is a partial failure where the effects are noticeable, but the component can still perform the required function though some functions can be compromised.
- Incipient Failure: This Failure is at the early stage of degradation and barely noticeable. Components can still perform the required function. It might result in degraded or critical failure if maintenance action is not taken.

The frequency of failure for WT components and the downtime is a crucial factor that needs a clear understanding. Many research efforts are carried out on failure analysis for WT components, yet, most of these reports are based on old wind turbine technologies (Reder et al., 2016). Ribrant and Bertling (2007) investigated the failure statistics from Finland, Sweden, and the German database. The result showed that the gearbox is the most critical component in the WT system due to higher downtime per failure as compared to other components (Ribrant & Bertling, 2007). Reder et al. (2016) carried our failure analysis on a 1MW DD WT. The result showed that the generator experiences a high failure rate caused by additional stress due to the absence of a gearbox. The control system and power module also have a large share of the failure, though the downtime caused is minimal (Reder et al., 2016).

The most completed dataset regarding reliability and maintainability was published by Carroll et al. (2016). The report "*Failure rate, repair time and unscheduled O&M cost analysis of offshore wind turbines"* by (Carroll et al., 2016) was based on 350 offshore wind turbine of 3 to 10 year and all installed in Europe. The report provided the various failure rate of WT components, the repair time and cost, and the required number of the technician for each component repair. These inputs are combined in Figure 16. The average wind speed offshore is about 12m/s compared to 8m/s average windspeed onshore, which makes the failure rate for OWT higher. The pitch system experiences 12.2%, which highest failure rate for OWT, whereas the generator has about a 12.1% failure rate. Other components that have higher failure include the gearbox and blade with 7.6% and 6..2%, respectively (Carroll et al., 2016). Component of the WT such as gearbox, blade, and the hub requires more time and technicians if a failure occurs because it would require an external crane for lifting, especially for a major replacement. In summary, OWT experiences about ten failures per year where minor repair, major repair, and major replacement are 80%, 17.5%, and 2.5%, respectively (Carroll et al., 2016).



(a)

	Pitch / Hyd	Other Components	Generator	Gearbox	Blades	Grease / Oil / Cooling Liq.	Electrical Components	Contactor / Circuit Breaker / Relay	Controls	Safety	Sensors	Pumps/ Motors	Hub	Heaters / Coolers	Yaw System	Tower / Foundation	Power Supply / Converter	Service Items	Transformer
■ Major Replacement	0.001	0.001	0.095	0.154	0.001	0.000	0.002	0.002	0.001	0.000	0.000	0.000	0.001	0.000	0.001	0.000	0.005	0.000	0.001
▧ Major Repair	0.179	0.042	0.321	0.038	0.010	0.006	0.016	0.054	0.064	0.004	0.070	0.043	0.038	0.007	0.006	0.089	0.081	0.001	0.003
▤ Minor Repair	0.824	0.812	0.485	0.395	0.456	0.407	0.358	0.326	0.355	0.373	0.247	0.278	0.182	0.190	0.162	0.092	0.076	0.108	0.052
▥ No Cost Data	0.072	0.150	0.098	0.046	0.053	0.058	0.059	0.048	0.018	0.015	0.029	0.025	0.014	0.016	0.020	0.004	0.018	0.016	0.009

(b)

	Hub	Blades	Gearbox	Contactor / Circuit Breaker / Relay	Generator	Power Supply / Converter	Yaw System	Other Components	Pitch / Hyd	Transformer	Controls	Electrical Components	Grease / Oil / Cooling Liq.	Heaters / Coolers	Sensors	Pumps/Motors	Service Items	Tower / Foundation	Safety
□ No Cost Data	8	28	7	5	13	10	9	8	17	19	17	7	3	5	8	7	9	6	2
▤ Minor Repair	10	9	8	4	7	7	5	5	9	7	8	5	4	5	8	4	7	5	2
▧ Major Repair	40	21	22	19	24	14	20	21	19	26	14	14	18	14	6	10		2	7
■ Major Replacement	298	288	231	150	81	57	49	36	25	1	12	18	0	0	0	0	0	0	0

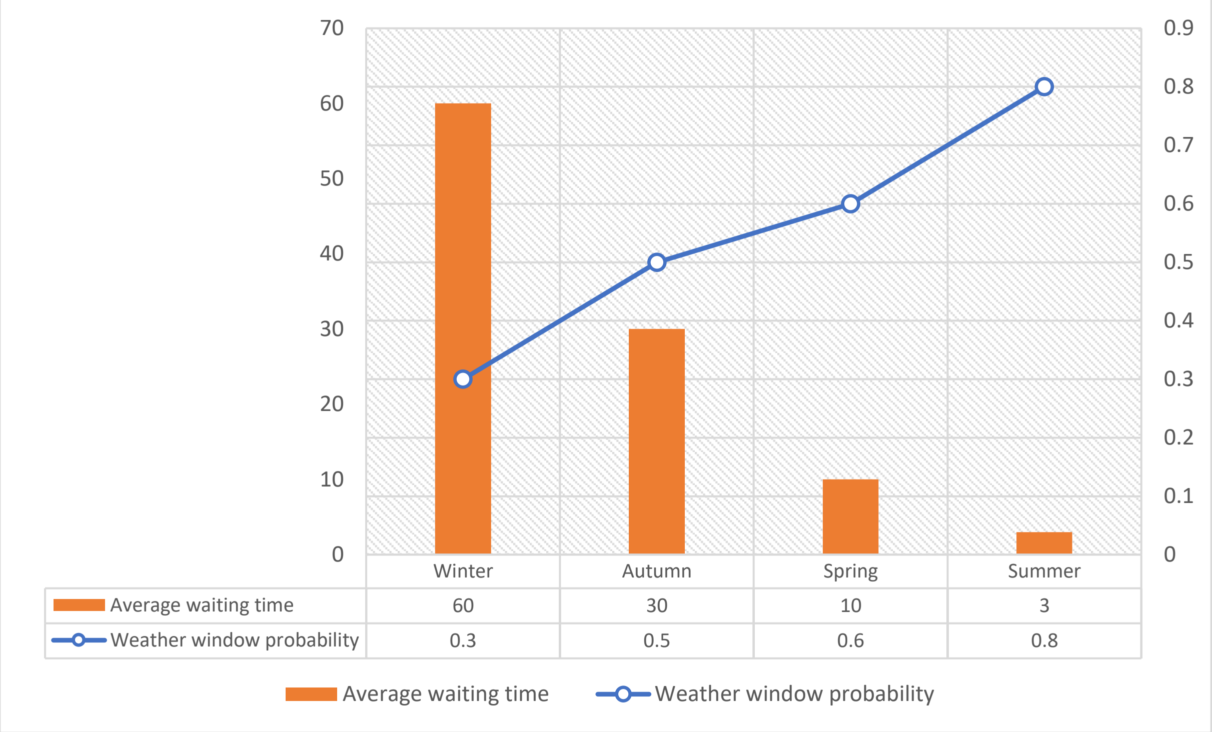
(c)

	Blades	Gearbox	Hub	Contactor / Circuit Breaker / Relay	Generator	Power Supply / Converter	Other Components	Yaw System	Pitch / Hyd	Electrical Components	Controls	Transformer	Heaters / Coolers	Grease / Oil / Cooling Liq.	Sensors	Safety	Pumps/ Motors	Tower / Foundation	Service Items
□ No Cost Data	2.6	2.2	2.4	2.0	2.4	2.7	2.3	2.4	2.8	2.4	3.2	2.8	2.7	2.0	2.7	2.0	2.5	2.3	2.2
□ Minor Repair	2.1	2.2	2.3	2.2	2.2	2.2	2.0	2.2	2.3	2.2	2.2	2.5	2.3	2.0	2.3	1.8	1.9	2.6	2.2
□ Major Repair	3.3	3.2	4.2	3.0	2.7	2.3	3.2	2.6	2.9	2.9	3.1	3.4	3.0	3.2	2.2	3.3	2.5	1.4	0.0
■ Major Replacement	21.0	17.2	10.0	8.3	7.9	5.9	5.0	5.0	4.0	3.5	2.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Figure 16. Failure rate (a), repair time (b), and number of technicians (c) for WT component (Carroll et al., 2016)

3.4.1. Maintenance Activities and challenges

The maintenance activities for an offshore wind turbine are a very challenging task due to so many uncertainties, especially the weather window. The weather situation is very crucial because some maintenance activities require good weather and several days to accomplish. Also, these maintenance operations cannot be conducted at wind speed greater than 12m/s and wavelength more than 1.5m. Figure 17 illustrates that the weather window is worst during the winter, where waiting time can reach up to 60 days (Jonker, 2017).



	Winter	Autumn	Spring	Summer
Average waiting time	60	30	10	3
Weather window probability	0.3	0.5	0.6	0.8

Figure 17. Weather window probability and waiting time (Jonker, 2017)

Some wind farm locations have limited good weather periods, so it is important to optimize the maintenance schedule to exploit the weather window. The planning and cost of maintenance are influenced by other factors such as the availability of repair materials, vessels, technicians, and the choice of maintenance strategy. When the maintenance schedule has been fixed, other requirements must be addressed, such as the number of technicians and qualifications, the type of vessel, and the best route for the vessel (Irawan et al., 2017). There are also legal restrictions influencing maintenance activities, such as the working hour restrictions, which are often not mentioned since they cannot be influenced by maintenance providers (Seyr & Muskulus, 2019).

Scheduling maintenance operations is complex with offshore wind farms. The service demand for the present generation of OWT is about 40 to 80 man-hours, and service visits are made depending on the planned maintenance strategy, usually every six months (Van Bussel et al., 2001). Major overhauling is mostly undertaken in the third or fifth year of operation and can take around 100 man-hours to complete. The experience gathered from the first Danish offshore wind farm, the "Tunø Knob wind farm," shows an annual service visit of 35 to 75 visits. The farm consists of 10 turbines, making it approximately 5 services per year for each turbine (Van Bussel et al., 2001).

Similarly, the SPARTA database gave some insight into the number of annual visits per turbine, as shown in Figure 18. The UK experienced about a 50% reduction in the average number of turbine transfers between 2014 till 2019, i.e., from approximately 15 visits to about 6 visits per turbine. These trips cover both corrective and planned maintenance campaigns, and a greater number of maintenance visits for the wind turbine are in the summer months, i.e., June – August. The maintenance activities for the newly developed wind farm are handled by the original equipment manufacturers (OEM) in the form of an equipment warranty, which is usually the first five years (SPARTA, 2019). This contract can be renewed for a longer period, whereas some project owners adopt a hybrid maintenance approach where OEM handles maintenance operations such as jack-up activity while farm owners cater for other activities. In some cases, the farm owner can contract out some maintenance operations to another independent service provider. Figure 19 illustrates the comparison between wind farm service visits per year with OEM and without OEM. Full OEM farm tends to have more visits during the summer period because the weather condition is more suitable for major maintenance activities while No OEM farm tend to have higher visit during the winter period (SPARTA, 2019).

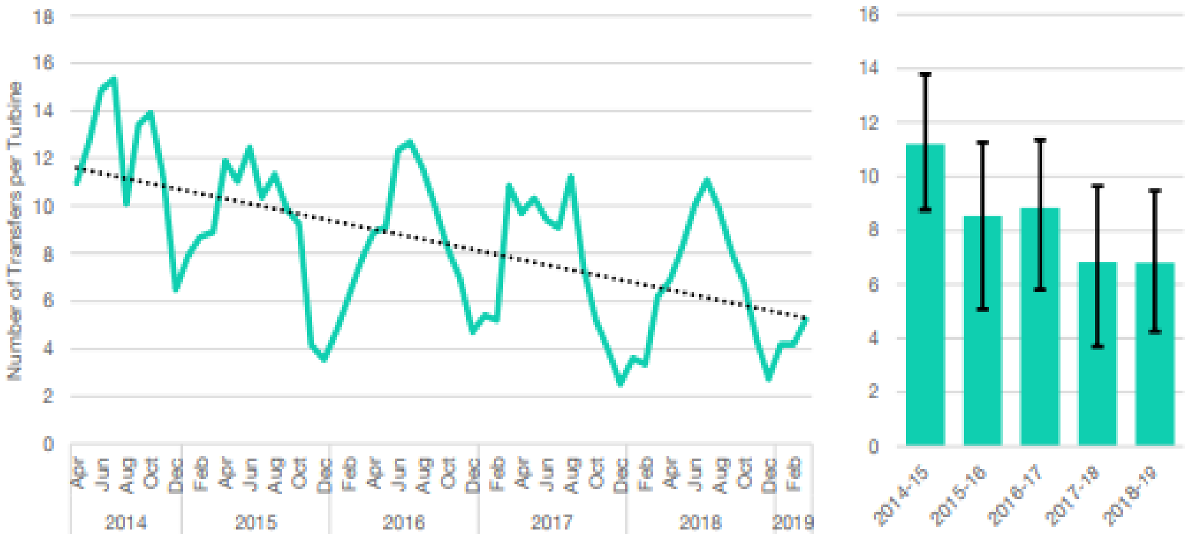


Figure 18. Number of Transfers per turbine (SPARTA, 2019)

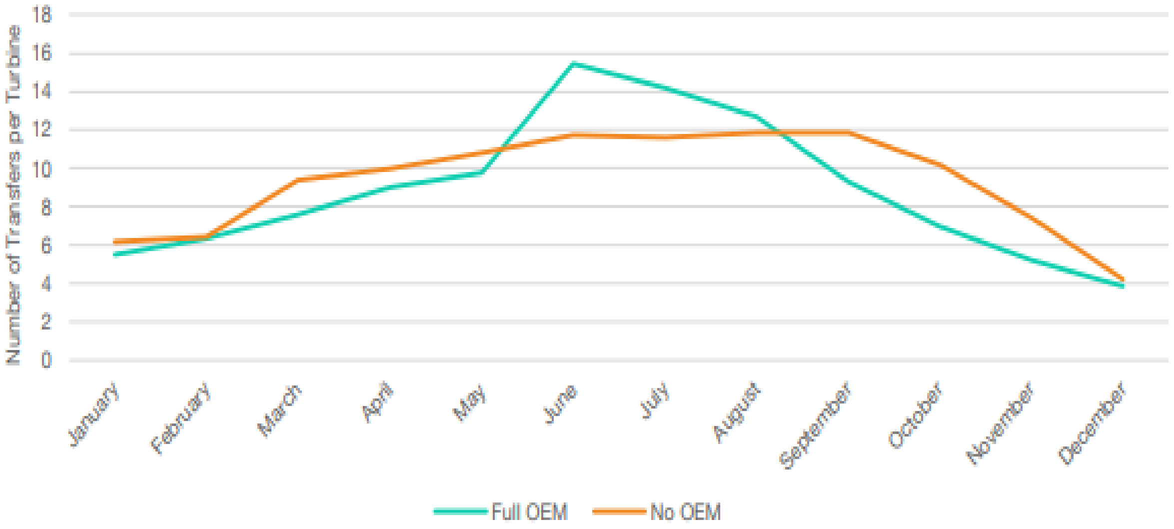


Figure 19. The average number of visits per Year with OEM and No OEM (SPARTA, 2019)

3.4.2. Maintenance Action

Different systems of wind turbines require different maintenance actions depending on the failure and the adopted maintenance policy. Maintenance actions are needed to restore, retain the functionality of the equipment. Anh et al. (2018) described four types of maintenance action which includes

- **Repair:** This involves maintenance actions aimed at restoring the equipment to its full or partial functional state; it could replacement of a component, such as a gearbox bearing, replacement of pitch system battery, e.tc.
- **Service:** This type of maintenance action is carried out to delay the degradation of equipment functions. For example, greasing, coating, etc.
- **Inspection:** Inspection actions are very important to map out or identify the equipment's state and investigate the cause of failure. Results from the Inspection operation help to decide on the necessary follow-up action to be taken. For example, visual inspection action is usually carried out on wind turbine blades to any failure such as cracks and corrosion
- **Improvement**: Maintenance action that aims to improve the functional reliability of equipment through both administrative and technical measures.

(Anh et al., 2018)

3.4.3. Maintenance categories

Maintenance activities for offshore can be categorized depending on the size of the component and their condition. According to report form (Le & Andrews, 2016), different maintenance action was categorized based on the size of the component and the supporting equipment required. It pointed out five types of maintenance action, as shown in Figure 20. It was also based on the degradation rate of the component and condition threshold (vibration and temperature monitoring). However, an onsite inspection is needed to confirm the actual condition. Each equipment condition is assigned to a specific type of maintenance, from normal working conditions to functional failure.

- Type 1: Comprises heavy lifting operation, which requires an external crane on jack-up vessels. For example, the blade replacement
- Type 2: Includes heavy lifting operation, which can be done using the internal.
- Type 3: Involves maintenance activities that require lifting of a small part of turbine component such as the pitch motor
- Type 4: Includes activities carried out in the wind turbine nacelle and did not require the use of the crane
- Type 5: Involves external maintenance activities on the tower, blade, and body of the nacelle, such as cleaning, coating, grinding, corrosion repairs, etc.

(Le & Andrews, 2016).

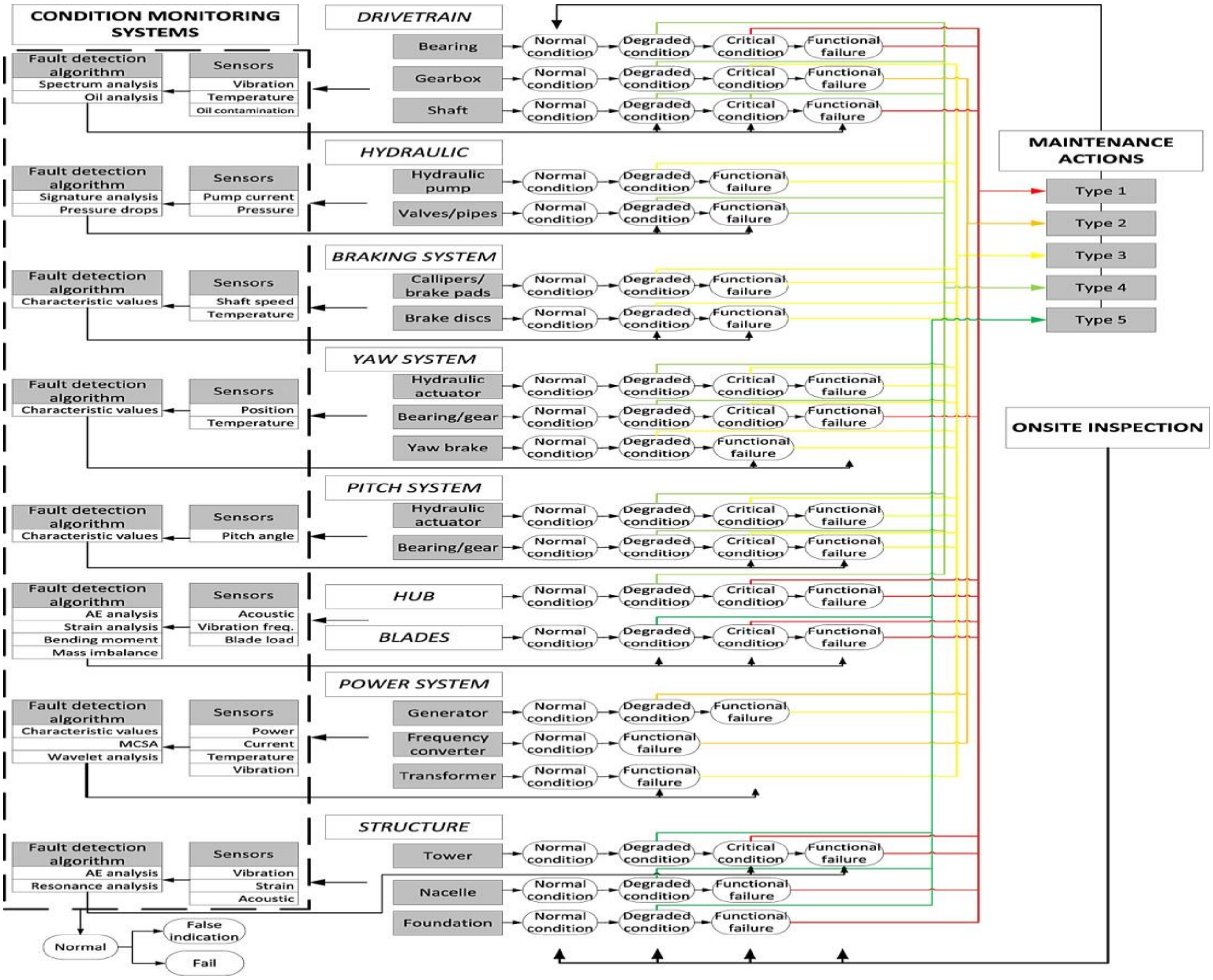


Figure 20. Asset state model and maintenance category (Le & Andrews, 2016)

3.4.4. Inspection Operation

The inspection operations for an offshore wind turbine cover a large part of operation and maintenance activities for offshore wind turbines. In general, the wind farm is designed to have a lifespan of 20years; therefore, inspection activities are required to map out the overall integrity of the wind turbine to identify or prevent failure. Typically, inspection operation for OWT is carried out by an experienced technician either visually by rope access or by a ground camera (Shafiee et al., 2021). Inspection activities offshore are quite expensive due to the associated circumstances such as the harsh windy conditions, long inspection time, and the safety risk it poses to technicians. Therefore, it is important to identify the failure modes and degradation process of WT structures and the critical areas for inspection in order to develop an effective inspection management program (Sheppard et al., 2010). Sheppard et al. (2010) listed out the main critical area of OWF facilities that requires inspection, as seen in Figure 21

- Subsea equipment
- Subsea structure
- Structural and access system above the water
- Above seawater equipment
- Blades (Sheppard et al., 2010)

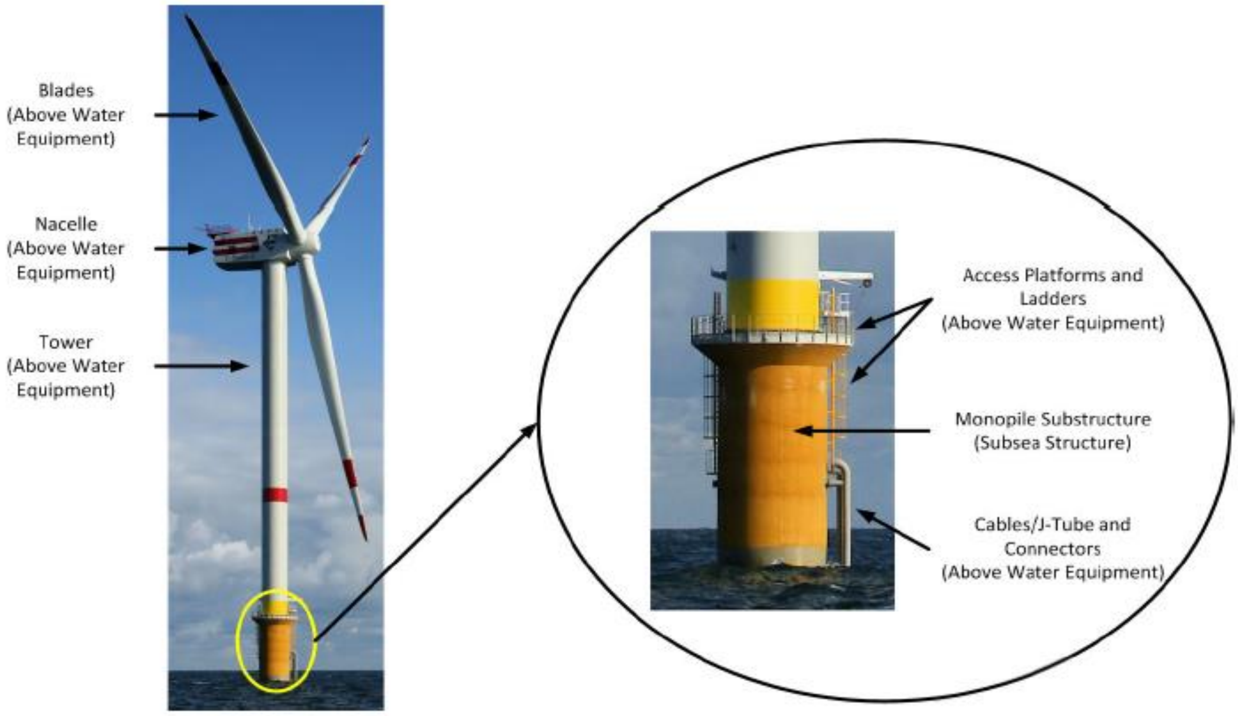


Figure 21. Typical offshore facility from the tower structure to blades (Sheppard et al., 2010)

If the floating structure is considered, then anchors and mooring lines would be included in the list. However, it is recommended to perform inspections at least once a year for structures and equipment above sea level (Martini et al., 2017). The Series of inspections are defined in table 6 based on existing standards and guidelines (Sheppard et al., 2010). The interval stated is based on the experience from the offshore industry and includes Annual, Intermediate, Extended, and Post-Event.

Table 6. Recommended inspection intervals (Sheppard et al., 2010)

Inspection area	Inspection Interval			
	Annually	Intermediate	Extended	Post-Event
Subsea Structure	1	3-5	6-10	As required
Subsea Equipment	N/A	3-5	N/A	As required
Above water structure	1	3-5	N/A	As required
Above water system	N/A	N/A	N/A	As required
Blade	1	3-5	N/A	As required

According to (Sheppard et al., 2010)

- The Annual inspection event mostly focuses on the above seawater activities where visual inspection is required. The above-water structure includes checking the splash zone for corrosion damage, checking the blade and nacelle for physical damage, coating breakdown, delamination, etc. Blade inspection can also be achieved remotely using binoculars or drones, though general visual inspection is sometimes required for confirmation (Sheppard et al., 2010).

- Intermediate inspection is carried out every 3-5 years and focuses on less accessible areas such as the subsea structure, bolts, and welded area. Here, the ROV is used to check for marine growth and any physical damage to the subsea structure and equipment.
- Extended inspection activities also focus on critical subsea structures and occur every 6 – 10 years. Here, more effort is made to investigate cracks and deviation on subsea concrete structures and the cleaning of marine growth.
- Post-event inspection activities are conducted based on the condition of the facility or due to unexpected events such as earthquakes and hurricanes. It included both the above water and subsea structures of the turbine.

Inspection activities and techniques used vary depending on the size of the wind farm. In larger OWF, it may not be possible to carry out inspection operations for all turbines in the farm due to cost implications. In this case, the overall status of all turbines in the farm are generalized using few reference turbines since there are located in the same area and are of the same design type. After an inspection operation, the results are review by an engineer to make adequate plans for addressing any issue found. Accessing the wind farm for inspection activities is usually through a workboat or helicopter. The Catamaran is the most used workboat mainly to transport technicians and small equipment to the OWF. During inspection operation, light services can be done, such as bolt tightening and some cleaning (Martini et al., 2017).

3.5. Theories About the Topic

A systematic literature review was done for the theories relating to the topic "Smart maintenance." Google Scholar (https://scholar.google.com/) database was used as a search engine for relevant literature. Table 7 presented the search keyword, the number of hits, and the number of relevant papers. The search was filtered using dates to streamline the search. Most of the literature found is generic and does not relate to offshore wind turbine applications. However, two previous thesis work relating to smart technology trends were found and were also used for this review.

Table 7. Systematic literature review

Search keywords	**Google Scholar**		**Search range**
	Number of hits	Relevant papers	
"Smart maintenance" AND "Offshore wind turbine"	14	1	2016-2021

3.5.1. Smart maintenance

In the attempt to describe the occurring improvements in many industries across the globe, several buzzwords such as Industry 4.0, Digitalization, Intelligent, and Smart are frequently used. Globally, all industries are facing different levels of transformation. Artificial intelligence (AI), sensors, robotics, etc., are the relevant topic area that shows the new way of carrying out business operations (Vagle, 2018). The word Smart is often used most especially when describing new technology and systems. Use cases include smart city, smart manufacturing, smart maintenance, smart building, smart supply chain, etc.

The demand for O&M of offshore wind farms is considered a key aspect in the development phase. Moreover, the challenges faced in the maintenance operation of an offshore wind turbine, such as cost, whether issue, safety risk, etc., have prompted wind farm owners to seek an improved technique to carry out maintenance activities, thereby using the term "***Smart maintenance***."

According to Langedijk (2016), the main idea of Smart maintenance is on how to bring about the integration of technology, machines, and humans to build an intelligent and innovative maintenance system (Langedijk, 2016). Smart maintenance (SM) combines various data sources such as real-time condition data, equipment criticality, service levels, availability of service technicians, travel time, weather condition, etc. Furthermore, it uses advanced data analytics to improve monitoring, optimize decision alternatives and optimize maintenance operations.

Failure can be predicted and addressed instead of carrying out unnecessary scheduled operations and a costly reactive maintenance approach (Cognite, 2021). The main target in employing a smart maintenance system is to carry out cost-effective maintenance work at an optimal time before the equipment losses its performance. Having access to real-time data for the industrial assets will allow the making of intelligent maintenance decisions, especially for critical equipment whose failure consequences are severe. Therefore, a smart system is required to monitor, remote access, and diagnose data needed for adequate maintenance management. One advantage of the monitoring system is that data collected can be segregated; each component, for example, in the wind turbines, is monitored separately. Therefore, it is easier to collect data on the behavior of each piece of equipment, such as the temperature, humidity, running time, etc. (Langedijk, 2016).

3.5.1.1. Condition monitoring system

The condition monitoring system (CMS) is needed to achieve effective condition-based maintenance. A fault prediction system must be applied, especially for rotational equipment in the WT system. The condition of the WT components is continuously evaluated by the CMS using data collection techniques such as oil analysis, vibration analysis, strain measurements (Task, 2017). The CMS provided the integration of autonomous online monitoring and fault detection, which gives an alert in the early stages of degradation of electrical and mechanical components of the WT to prevent major damage from occurring. The repair action required needs to be planned in time and taken into account the weather condition, which can hinder the maintenance operation (Hameed et al., 2009). Figure 22 illustrates the process of condition monitoring. Sensors are used for data acquisition to define the current state of the equipment being monitored, the signal is processed, and relevant features are extracted, such as the frequency (Task, 2017). The current state of the equipment obtained via online monitoring and stored historical data is combined for diagnosis (detection) and prognostic (prediction).

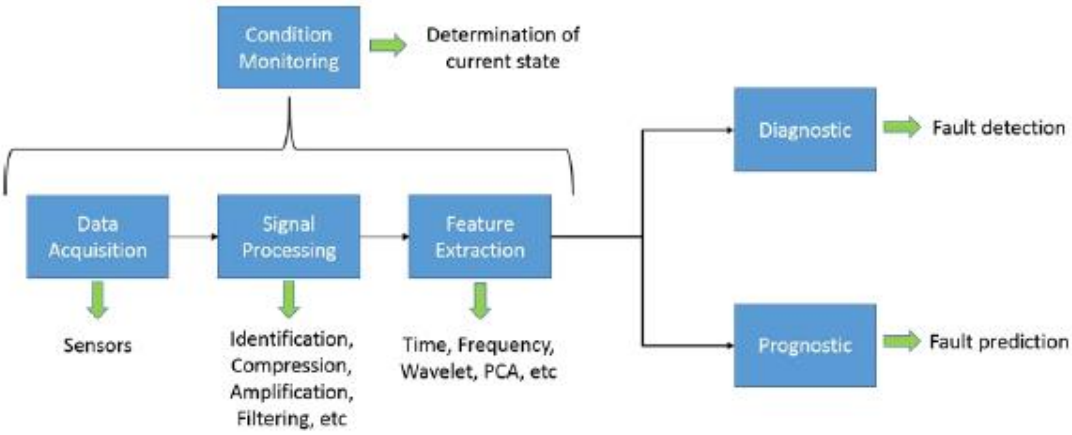


Figure 22. Condition Monitoring process (Task, 2017)

3.5.1.2. Predictive maintenance

Maintenance operation today focuses more on achieving a Predictive maintenance strategy where equipment is not repaired too early when it is in good condition nor repaired when it has failed, but repair should be done when needed in time. The optimal time can be when the effect on the failure is noticeable, but the equipment is still safe to run till the repair time suitable for the company. In most cases, when there is a planned shutdown, companies can take advantage of such an opportunity to carry out maintenance on components showing earlier signs of failure; this can also be referred to as Opportunistic maintenance (Sglunda, 2016).

Predictive maintenance applies a model based on both statistical and analytical methods to predict future equipment behavior. Modern wind turbines are now equipped with prognostics and health management technologic (PHM) to assess the reliability of critical equipment such as the gearbox, blade, and bearing based on the remaining useful life (RUL). Then, predictive maintenance operations are carried out to restore the equipment before it fails. Lei et al. (2015) evaluated the option for predictive maintenance created by the PHM for several WT using a simulated real options analysis (ROA). Here, the option for predictive maintenance is triggered when the RUL of the WT equipment is predicted; therefore, the option is utilized if predictive maintenance is applied; if not, then the option expires, and the option value returns to zero (Lei et al., 2015). However, suppose the maintenance trigger is to be utilized. In that case, the decision to carry out the maintenance action depends on how long the decision-maker is willing to wait, which is also influenced by the weather window.

Prediction horizon

The time interval for which the applied model provides a good prediction can be called the prediction horizon (Task, 2017). If the condition monitoring system gives a good horizon, it cannot be said to be exact; however, it has the required level of uncertainty and correctness that matches the intention for the application. As shown in the figure below, different models have different prediction horizon which ranges from short to long. The shaded green area presents the main application area of the model.

Table 8. Prediction horizon of different models (Task, 2017)

Model	**Short term**	**← Prediction horizon →**		**Long term**
	<<MTTF	<MTTF	MTTF	≥2 MTTF
Lifetime distribution		🟩	🟩	
Failure rate models			🟩	🟩
Physical models		🟩	🟩	
Stochastic degradation models		🟩	🟩	
Machine learning	🟩	🟩		
Stochastic models		🟩	🟩	🟩

3.5.2. Technology trends

work has identified several technologies which can be used to enhance wind turbine maintenance activities. The evaluation of emerging Innovation technologies for offshore wind turbine maintenance was presented in (Christensen, 2018a) (Hummervoll, 2018) though the result does not necessarily reflect a better area of investment for project owners. Smart technology trends can be categorized into

- Digitalization: Digital twin, Smart contracts
- Connectivity: Internet of things, 5G Network, Big data, Cloud computing
- Sensorization: Augmented reality, Virtual reality
- Autonomization: Machine learning, Autonomous underwater vessels, Rotors, Drones

3.5.2.1. Autonomization

There are possibilities of applying an Autonomous solution for some maintenance activities in OWF, for example, inspection operation. Autonomization is about using intelligent modern technologies that permit operation without being controlled by humans, such as autonomous underwater vehicles (AUV), Drones, and Repair robots. These technologies are equipped with sensors, Artificial Intelligence (AI), and analytical capabilities, allowing them to make decisions independently.

Automation aims to cut down the cost required for maintenance work, repair time, and turbine downtime, directly affecting production and revenue. For example, a Visual Inspection of wind turbines (WT) components such as rotor blades and tower can take much time to complete, especially during bad weather. However, the time, cost, and risk involved in these maintenance activities can be significantly reduced using a robotic platform to aid remote inspection and data collection from the WT in real-time.

Figure 23. Robotic for the inspection of offshore wind farms (Shafiee et al., 2021)

Using an unmanned aerial vehicle (UAV) such as a drone for inspection has become popular in the offshore wind energy industry. As shown in Figure 23, drones are transported to the offshore wind farm (OWF) on a vessel or by helicopter and operated remotely to fly around the turbine. Drones can reduce the cost of O&M, increase efficiency, and minimize downtimes (Shafiee et al., 2021). Stout and Thompson (2019) illustrated the five steps involved in using drone inspection, including the creation of defect standards, data collection, inspection, report matrix, and output visualization (Craig Stout, 2019). Frederiksen and Knudsen (2018) presented an analysis illustrating the opportunities and barriers in employing a drone-based solution for OWF in Denmark (Frederiksen & Knudsen, 2018). Though Drone is suitable for replacing risk jobs, there is still more improvement, such as operational inspection and incorporating machine learning algorithms for classification of fault during the inspection. Bernardini et al. (2020) also presented the scenario of using a fully autonomous crawler robot that consists of a flexible arm capable of performing blade inspection, maintenance and repair (IMR), surface treatment, and cleaning tasks (Bernardini et al., 2020).

AUV has gained huge development for subsea inspection recently, although it is regarded as too expensive. It can carry out autonomous maintenance and repair of the subsea components and cable. Currently, remotely operated vehicles (ROV) and human divers are commonly used for subsea inspection operations.

Other modern technologies have also been identified to have great potential for OWT maintenance, such as augmented reality for remote maintenance support. This system is utilized by customizing the AR software into a smart glass to enable an expert to follow up and aid technicians on-site during a maintenance operation (Christensen, 2018a).

3.5.2.2. Big Data Analytics

A good monitoring system can be achieved by equipping industrial assets with sensors that collect enormous data depending on the number of components monitored. These data can come in various forms, unstructured or structured, continuous, and irregular. Typically, the data is so large to analyze traditionally and requires very scarce experts. However, advancements in technology have brought about “Big-data” which is concerned with extracting meaningful data from many datasets using predictive analytics (Christensen, 2018b). Big Data technology is said to have great potential in offshore wind application, and it relies on four characteristics which include

- Monitoring: Sensors enable adequate tracking of asset condition, operation and able to give out an alert and notification of any variations
- Control: Able to control equipment function through the embedded software in the asset
- Optimization: control and monitoring abilities enables algorithms to optimize equipment operation and provide predictive diagnosis
- Autonomy: Permits independent operation through the combination of monitoring, control, and optimization

(Porter & Heppelmann, 2014)

3.5.2.3. Machine learning

The idea of Machine learning is to enable machines to learn from data, identify patterns and make a decision autonomously. The machine learning process is grouped into four steps: the data acquisition, where several datasets are cleanout. Then, relevant signals are extracted from the dataset. The third step is to select the model based on the task or issue. The last step is the validation step, where the task-specific key performance measure (KPI) is used to evaluate the dataset (Stetco et al., 2019).

3.5.2.4. Digital twin

Recent development in the wind industry is channeled towards the development of siting wind farms further away from shore to utilize more wind resources. To optimize the turbine performance and reduce downtime and maximize production, operators are turning towards digitalization. One such technology is digital twins, a copy of the physical turbine that enables real-time monitoring of the project and maintenance planning (Gerdes, 2020). A virtual model is built based on the physical model and is connected using a sensor to generate real-time monitoring data. The digital twin is one of the largest promising technology from industry 4.0. The digital twin will allow the operator to control the asset function better and provide better safety and sustainable operations during maintenance. Aker solution is currently working with Cognite to build a Digital model for a floating offshore wind turbine that it plans to build off the coastline of California. The plan is to generate data insight from real-time monitoring of typical equipment to reduce O&M cost, increase power production and overall performance throughout the project's lifetime (Gerdes, 2020. The future of simulation lies in the digital twin, and the development of more advanced hardware will provide more effective diagnostic and prognostics system (Vagle, 2018)

3.6. Theories about the used methods

3.6.1. Risk-based maintenance

Risk-based maintenance (RBM) is an approach whereby maintenance events are developed based on the critical or risk profile of the equipment (Priyanta & Zaman, 2021). The maintenance activities for the equipment depend on the failure mode for the equipment. For example, in the oil & gas sector, there are several types of equipment, and these equipment have different risk levels. Technically, high-risk equipment is prioritized over low-risk equipment. The RBM is established in the Norsok-Z-008 standard for oil & gas. The steps in the RBM include the technical hierarchy, functional hierarchy & consequence classification, FMEA, and maintenance task selection.

3.6.1.1. Technical Hierarchy

According to Tanver (2012), the WT taxonomy structure or the Technical hierarchy is required for proper failure location and identifying the focus area for repair and other maintenance activities to optimize availability (Tavner, 2012). The taxonomy structure illustrates the main features of the wind turbine system using standard terminology, and this taxonomy is required for adequate maintenance management, which should be established at the early phase of design. Although efforts have been made towards developing the wind turbine taxonomy, their principal structure and level details differ (Kaidis, 2014). One of such is the taxonomy presented by the Sandia National laboratory.

The information available is the main criteria in developing the taxonomy, and the component performing the same function should be grouped together. The taxonomy developed by the Relia wind Consortium is mostly used due to the application of data analysis in the Relia wind project. The taxonomy is based upon five levels, and the example of the classification is shown in Figure 24

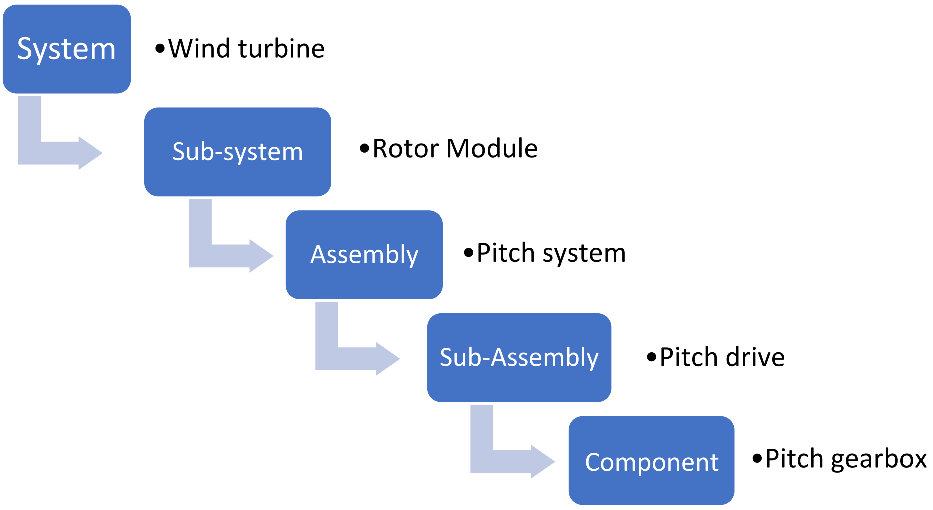


Figure 24. Wind turbine Taxonomy structure (Tavner, 2012)

3.6.1.2. The functional hierarchy and consequence classification

According to Norsok-Z-008 (2001) standard, the functional hierarchy and consequence classification is required in order to establish and manage maintenance activities following a risk base decision approach. In this procedure, the Main function and the system equipment's sub-function are identified and classified based on their criticality level. The risk matrix is used to determine the criticality of equipment based on four parameters such as safety, environment, repair cost, and production. There is some required precondition to establishing the criticality analysis, such as the technical documentation describing the plant capacity, operating conditions. Technical diagrams such as P&ID and one-line diagrams are also necessary to set up this process (NORSOK-Z-008, 2001). The process and steps for carrying out functional hierarchy and consequence classification are explained in detail in the Norsok-Z-008 standard.

3.6.1.3. Failure Mode and Effect Analysis (FMEA)

The FMEA a method used to identify the failure modes, root causes, and their effect on the performance of a system(Catelani et al., 2020). It is part of the reliability analysis in the design stage of a system due to the consideration of failure rates (Tavner, 2012). The Failure Mode Effect and criticality analysis (FMECA) process is an extension of the FMEA, which identifies the dominant failure modes of the maintenance significant items (MSI) (Task, 2017). The criticality level in FMEA is grouped into Low, Medium, and High criticality, where preventive maintenance is assigned to High and medium criticality. In contrast, corrective maintenance is assigned to low critical components or, as described by the original equipment manufacturer (OEM)—structuring the FMEA in terms of predefined root causes of failure types and effects etc., aids in accessing and optimizing maintenance intervals (Task, 2017). The manufacturers define the failure mode and root causes for the sub-system of the wind turbine. However, a more general failure mode and root causes are adopted to avoid a widespread failure mode that could be generated based on manufacturer experience and knowledge (Tavner, 2012).

Several studies have investigated the failure mode and effect analysis of wind turbines (WT). Scheu (2019) identified 337 failure modes of the main systems of the WT, which could aid the development of a condition monitoring system for the most critical system and identifying the operation and maintenance techniques. However, about one-third of the identified 337 failure mode is related to the substructure (Scheu et al., 2019). Another study by Shafiee (2014) carried out FMEA analysis on onshore and offshore wind turbines of the same type. As described in Figure 25, both systems' risk is similar, though they are notable differences in the RPN of some systems. For example, the RPN number for the tower is 35 units higher in the offshore WT. Also, the RPN for the gearbox is higher than the rotor blade for the onshore WT, whereas both score the same RPN in the offshore WT (Shafiee & Dinmohammadi, 2014).

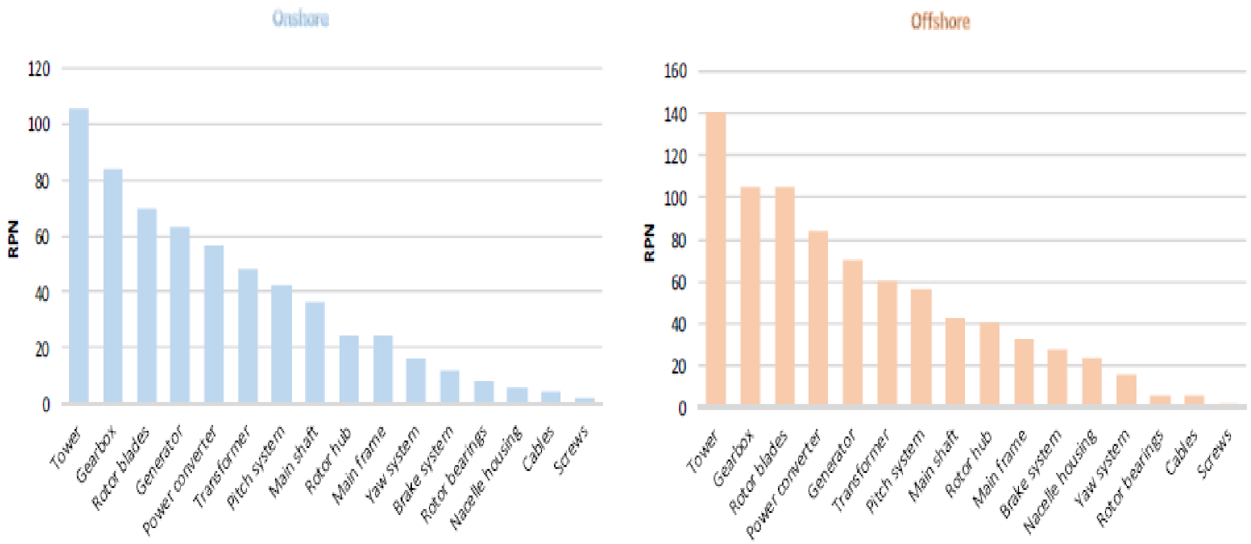


Figure 25. RPN values for onshore and offshore wind turbine sub-assemblies (Shafiee & Dinmohammadi, 2014)

A quantitative Risk-base-FMEA was presented by (Kahrobaee & Asgarpoor, 2011), considering the incurred failure costs and the failure probabilities. This approach was applied for a 3MW direct-drive WT where the generator, control system, and mechanical brake were identified are the most critical part of the direct-drive turbine, respectively. However, it is important to note that different FMEA team members have different opinions due to their diverse backgrounds; therefore, assessment information should be well modeled using existing structures (Shafiee & Dinmohammadi, 2014).

The process for FMEA, as outlined by Pillay and Wang (2003), is divided into several steps, which as described in Figure 26

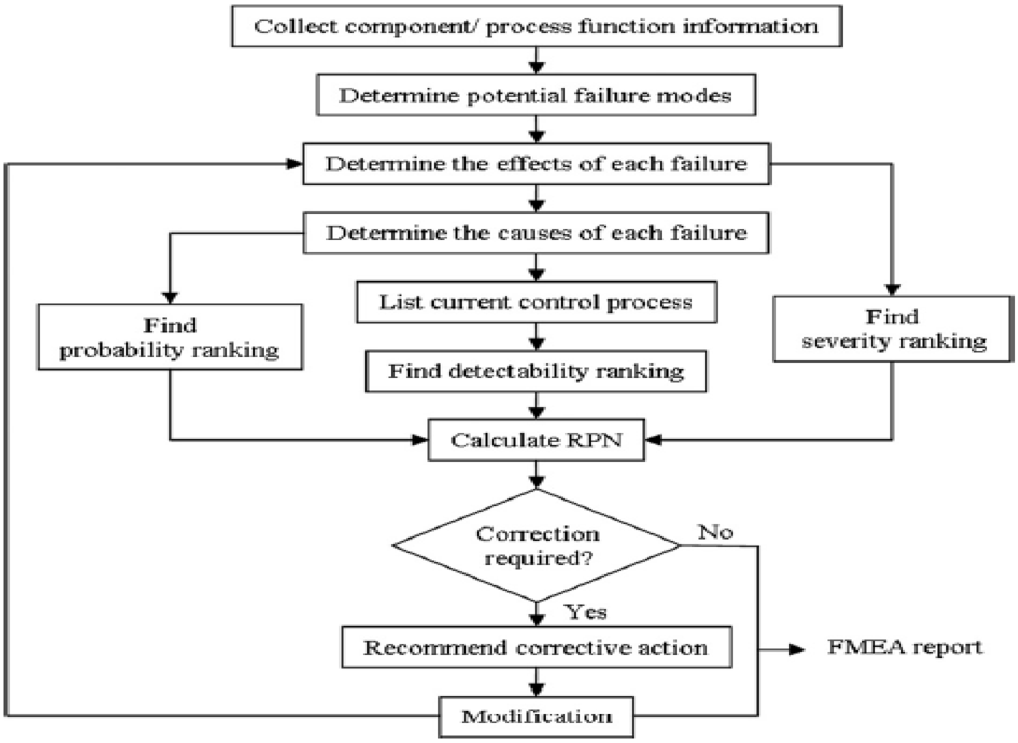


Figure 26. FMEA process (Pillay & Wang, 2003)

According to Tanver (2012), the steps can be briefly summarized as follow,

- The study of the system and break down of the system into units, sub-units, and system. This involves a comprehensive understanding of the system (wind turbine) and its taxonomy
- Assign failure mode and root cause to each unit of the system and sub-units
- Specify the end effects of the failure mode and assign the severity and occurrence and detection must be assigned to the root cause
- The Risk priority number (RPN) is calculated by multiplying the ranking of the severity, occurrence, and detectability, i.e., Severity x Occurrence x Detectability = RPN

3.6.1.4. Maintenance task selection and Manning study

The assigning of a maintenance action is an important aspect to be well considered to ensure the reliability of the WT system. Difference maintenance action is assigned to the components of the WT depending on the failure mode. For each failure mode, a decision is made to carry out preventive maintenance or allow the system to run to failure and then carry out corrective maintenance (Task, 2017). The number of personnel required and manning hour is estimated based on the maintenance tasks. Decision logic, such as the example shown in Figure 27, is used to guide the process.

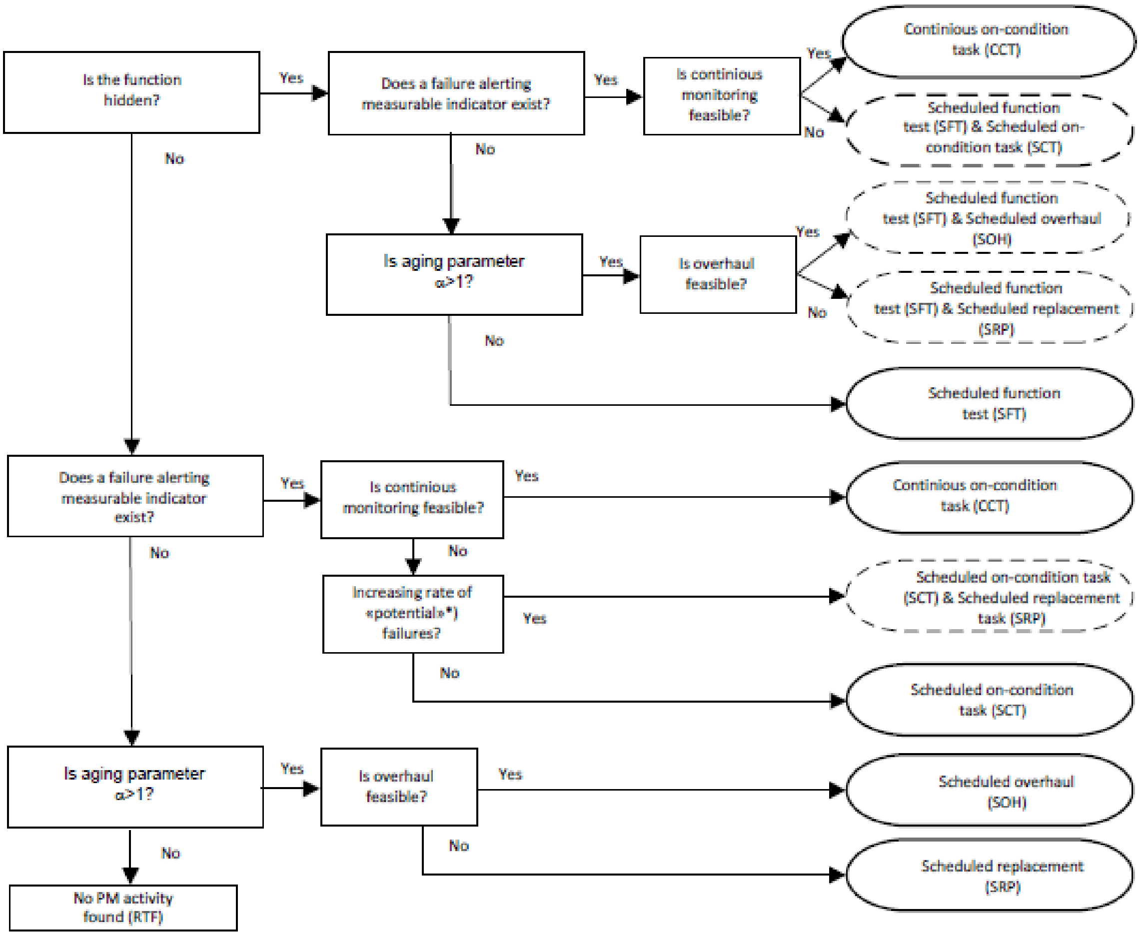


Figure 27. Maintenance task decision logic (Task, 2017)

3.6.2. Modeling and Simulation

To predict the behavior of a physical system and the impact throughout their life, Modelling and simulation tools are utilized. One of the main enabling technologies of industry 4.0 lies in Modelling and simulation, which is vital in developing digital twin and prescriptive analytics in real-time (El-Thalji, 2019). As illustrated in Figure 28, several simulation approaches/ paradigms for industrial engineering include Agent-based, system dynamics, and discrete events (Anylogic, 2021). However, development has been made towards multi-modeling methods that integrate different modeling approaches to eliminate individual modeling methods. For example, Anylogic tool enables the use of all three simulation paradigms seamlessly. The best description of these modeling methods is given in "*The Big Book of Simulation Modelling-Multimethod Modelling with Anylogic 6*" by Borshchev, A. (2013).

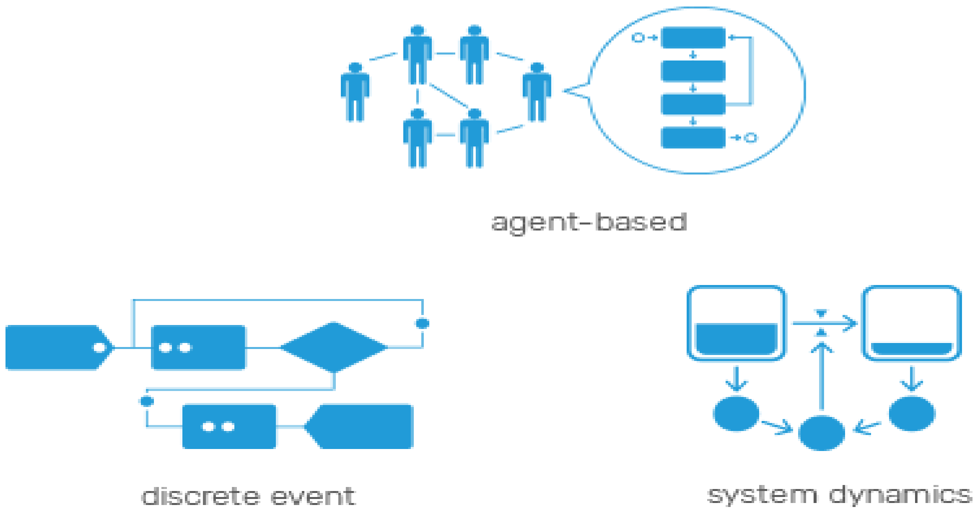


Figure 28. Different simulation methods (Anylogic, 2021).

Chapter 4

4.0. Data collection

This chapter presents the case description, the data sources, and the method of collection adopted for the different steps of the research methodology. It also presents the questions used for the interview conducted for this research.

4.1. Case Description

The maintenance concept for the wind turbine system will be explored to determine how applicable is smart technologies in the maintenance of offshore wind turbines. The selected system for this research is a reference direct-drive wind turbine model with a fixed-bottom monopile foundation. Though the focus will mainly be on the components inside the wind turbine nacelle. The development of the smart maintenance concept will be based on the selected critical equipment in the turbine.

The data used for this research combines both primary and secondary data sources. Systematic literature review (books, articles, and reports) was done using online databases such as Google Scholar to collect relevant data relating to the case topic. Information was also gathered through interviews with stakeholders, discussion with study groups, and the case company supervisors. Table 9 shows the steps adopted to achieve the goal of this research and the data sources and method of data collection.

Table 9. Data collection

Steps		Data source	Data collection	Reliability and Validity actions
1	System description	Online Literature review	Literature review	Online literature, study group, Expect opinion
2	Technical hierarchy of the selected Turbine design	Online Literature review, Relia wind taxonomy	Literature review,	Checking traceability with ISO 14224 standard, Expert opinion
3	Functional Hierarchy and consequence classification	Online literature, P&ID, NORSOK Z-008 standard, Risk decision criteria, Risk matrix	Expert opinion, Focus group	Expert opinion, study group
4	Failure mode and effect analysis (FMEA)	Online literature. ISO 14224 Standard, FMEA Rating scale	Retrieve numerical data	Expert opinion, study group
5	Manning study	Online literature SPARTA database, Interview, Model input data	Interviews with stakeholders Retrieve numerical input data	Experts opinion, study group
6	Smart maintenance study	Expert perception about smart maintenance, Literature review	Focus group, Retrieve document	Expert opinion,
7	Comparison study	Simulation result from step 5 and 6	Simulation results from step 5 and 6	Expert opinion, study group

1. **The system description:** The system is the Direct-drive WT which is different from the typical gearbox wind turbines. Currently, the case company does not have this type of WT system. Therefore, I have depended on online literature to understand the system, the main parts, and how it operates.

2. Technical Hierarchy: The step is required to understand how the system is technically built by grouping the system component according to their hierarchy level. However, I have relied on online literature relating to wind turbine taxonomy. The Taxonomy used was developed by Relia wind Consortium and was a reference by (Tavner, 2012), and a similar taxonomy was presented by (Kaidis, 2014). I decided to use by reference to obtain a better

3. Functional Hierarchy and consequence classification: The requirement in the step is to define each Wind turbine system's main function and sub-function and classify them according to their level of criticality. Information was derived from the Norsok-Z-008 standard. The example listed in this standard is more related to the oil and gas sector. Base on Engineering judgment and interpretation of the standard, I created some main functions to match the wind turbine system. The risk decision criteria used for the consequence classification were obtained from the case company (Aker solutions). To complete the consequence classification, safety, environment, cost, production, and failure frequency parameters have to be defined. For this reason, I have used the reference dataset published by (Carroll et al., 2016).

4. Failure Mode and Effect analysis: This step is the requirement to further analyze the equipment with high or criticality level from the consequence classification. I adopted the failure mode as described ISO 14224 standard. Table X in the analysis chapter shows the list of failure modes used. The rating scale presented by Arabian-Hoseynabadi et al. (2010) will be used to rank the severity, occurrence, and detection parameters. I have also made reference to the FMEA from (Shafiee & Dinmohammadi, 2014) to compare the numbers used in the rating scale.

5. **Maintenance tasks selection / Manning study:** The develop the maintenance concept, information about the maintenance activities is needed. Based on my supervisor's recommendation, I have conducted a semi-structured interview. The interview process was carried out on LinkedIn, where 5 participants were targeted. The participant was selected by focusing on individuals with experience and background knowledge in the wind Industry. I also got the opportunity to have a physical meeting with the Project manager of Espeland Energie to get an overview of the typical maintenance activities. The company is located in Egersund, Norway, and they carry out maintenance and inspection operations for the wind turbine. Table 10 presents the list of questions that were used in the interview. The answer to these questions will be provided in Appendix A.

Table 10. Interview questions

Relevant topics	Questions	Comment
Inspection operation	1. How many Inspection campaigns per year for offshore wind turbine	Understanding the purpose and key activities for the inspection operation
	2. Is there an inspection campaign for specific equipment in the wind turbine	
	3. What is the specific purpose for each inspection operation	
	4. What component is to be inspected in the turbine (external and internal)	
	5. What other activities happen during the inspection operation	

Maintenance operation	7. How many planned maintenance campaigns per year	Understanding the key activities during the maintenance operation
	8. what are the typical task/ activities during each maintenance	

6. Smart maintenance study: The main data source for this step was from an employee in Aker solution who provided a list of smart maintenance use cases that apply to offshore wind. These use cases will be used to develop the smart maintenance workflow.

7. Comparison study: The step is required to carry out comparative analysis based on the simulation result from the baseline manning study and the smart maintenance study.

4.2. Limitations

The following are some of the limitation concerning the data collection

- Two out of five of the participants targeted responded to the interview questions.
- Most of the responses from the interview were not comprehensive due to the issue of confidentiality; therefore, some information is taken from online literature.
- Another limitation is the lack of standards related on wind energy. Most adopted standards are based on the oil & gas sector, making it challenging to implement for the wind industry.

Chapter 5

5. Analysis and Results

This section discusses each step in the analysis carried out to achieve the goal of the thesis, and it presents the results of each step. Figure 29 *below illustrates the workflow of this chapter which is aligned with the methodology as stated in chapter 2. Each step will be followed accordingly from step 1 to step 7.*

In summary, step 1 to 5 is regarded as the baseline concept which follows the Risk-based maintenance approach while step 6 to 7 is the improved concept based on the Smart maintenance study.

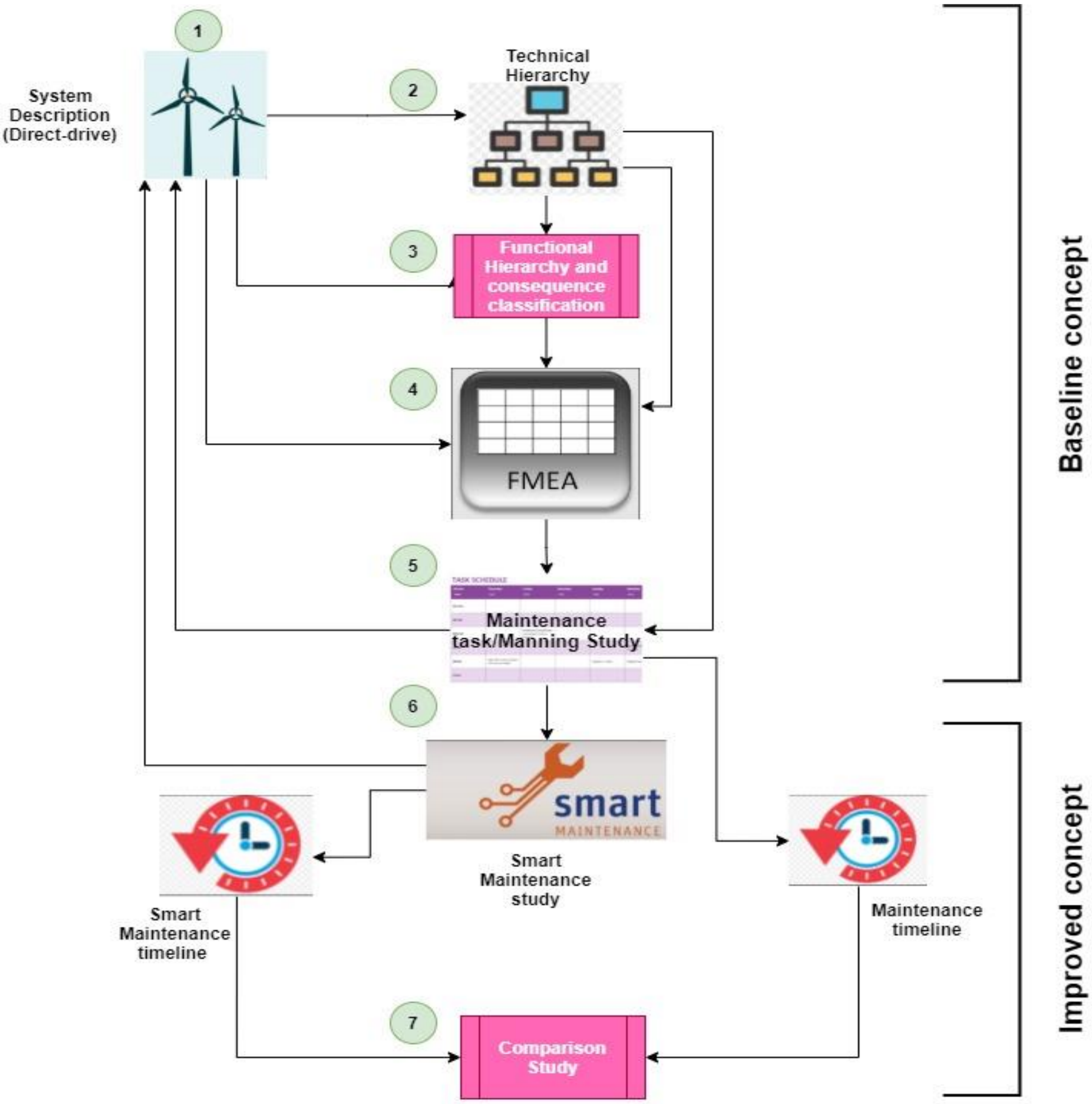
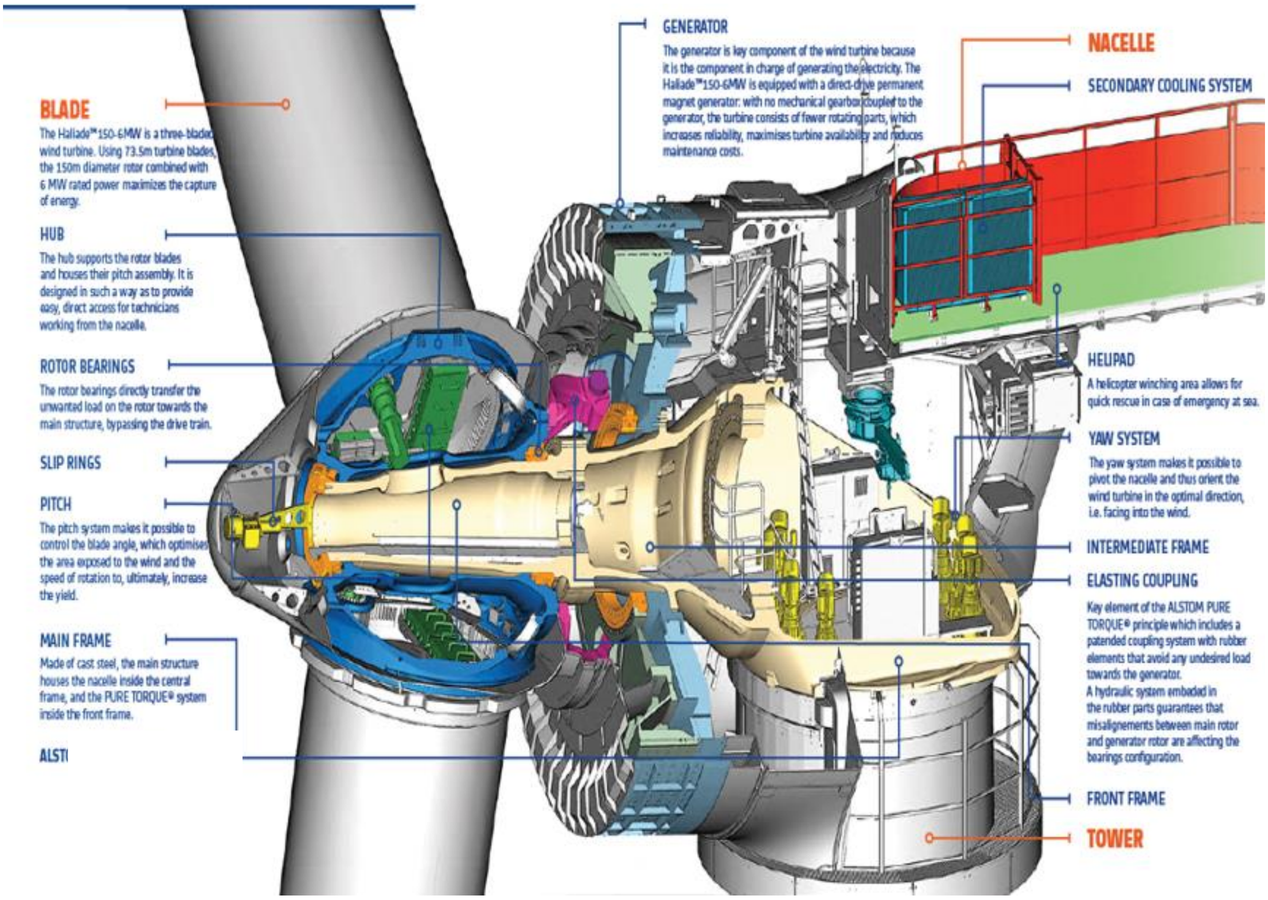


Figure 29. The Analysis workflow

5.1. The Selected System Description (Wind turbine Direct-drive)

The selected system for the research is the 6MW direct-drive Wind Turbine which is shown in Figure 30. It also describes the different parts of the turbine, such as the rotor, blade, generator yaw system, e.tc. Section 3.2.3 of the report presented a comparison between gear drive and direct drive turbine where the trend and issue with both drive trains were highlighted.

The technical specification includes:
Rate power – 6000KW
Blade diameter – 75m
Swept area – 18,600m^2
Cut-in air – 3m/s
Cut-out air – 25m/s
Generator – Direct Drive permanent magnet
Power regulation - Pitch regulated, variable speed



BLADE
The Haliade™150-6MW is a three-bladed wind turbine. Using 73.5m turbine blades, the 150m diameter rotor combined with 6 MW rated power maximizes the capture of energy.

HUB
The hub supports the rotor blades and houses their pitch assembly. It is designed in such a way as to provide easy, direct access for technicians working from the nacelle.

ROTOR BEARINGS
The rotor bearings directly transfer the unwanted load on the rotor towards the main structure, bypassing the drive train.

SLIP RINGS

PITCH
The pitch system makes it possible to control the blade angle, which optimises the area exposed to the wind and the speed of rotation to, ultimately, increase the yield.

MAIN FRAME
Made of cast steel, the main structure houses the nacelle inside the central frame, and the PURE TORQUE® system inside the front frame.

ALST

GENERATOR
The generator is key component of the wind turbine because it is the component in charge of generating the electricity. The Haliade™150-6MW is equipped with a direct-drive permanent magnet generator: with no mechanical gearbox coupled to the generator, the turbine consists of fewer rotating parts, which increases reliability, maximises turbine availability and reduces maintenance costs.

NACELLE

SECONDARY COOLING SYSTEM

HELIPAD
A helicopter winching area allows for quick rescue in case of emergency at sea.

YAW SYSTEM
The yaw system makes it possible to pivot the nacelle and thus orient the wind turbine in the optimal direction, i.e. facing into the wind.

INTERMEDIATE FRAME

ELASTING COUPLING
Key element of the ALSTOM PURE TORQUE® principle which includes a patended coupling system with rubber elements that avoid any undesired load towards the generator.
A hydraulic system embaded in the rubber parts guarantees that misalignements between main rotor and generator rotor are affecting the bearings configuration.

FRONT FRAME

TOWER

Figure 30. A 6MW Direct drive Wind Turbine (Dvorak, 2016) windpower

5.1.1. Operating Case Scenario

Figure 31 illustrates the operating case of the direct-drive wind turbine. The wind initiates the entire process of energy production. Once the wind speed reaches the cut-in speed of 3m/s, the blade starts to rotate, which rotates the rotor hub/spinner of the turbine. Unlike the typical conventional wind turbine, the rotor is directly connected to the generator by the main shaft.

The main shaft transfers the low-speed mechanical energy from the wind to the generator. The direct-drive generator comprises several magnetic poles, making it able to achieve the desired output voltage without requiring high-speed rotation.

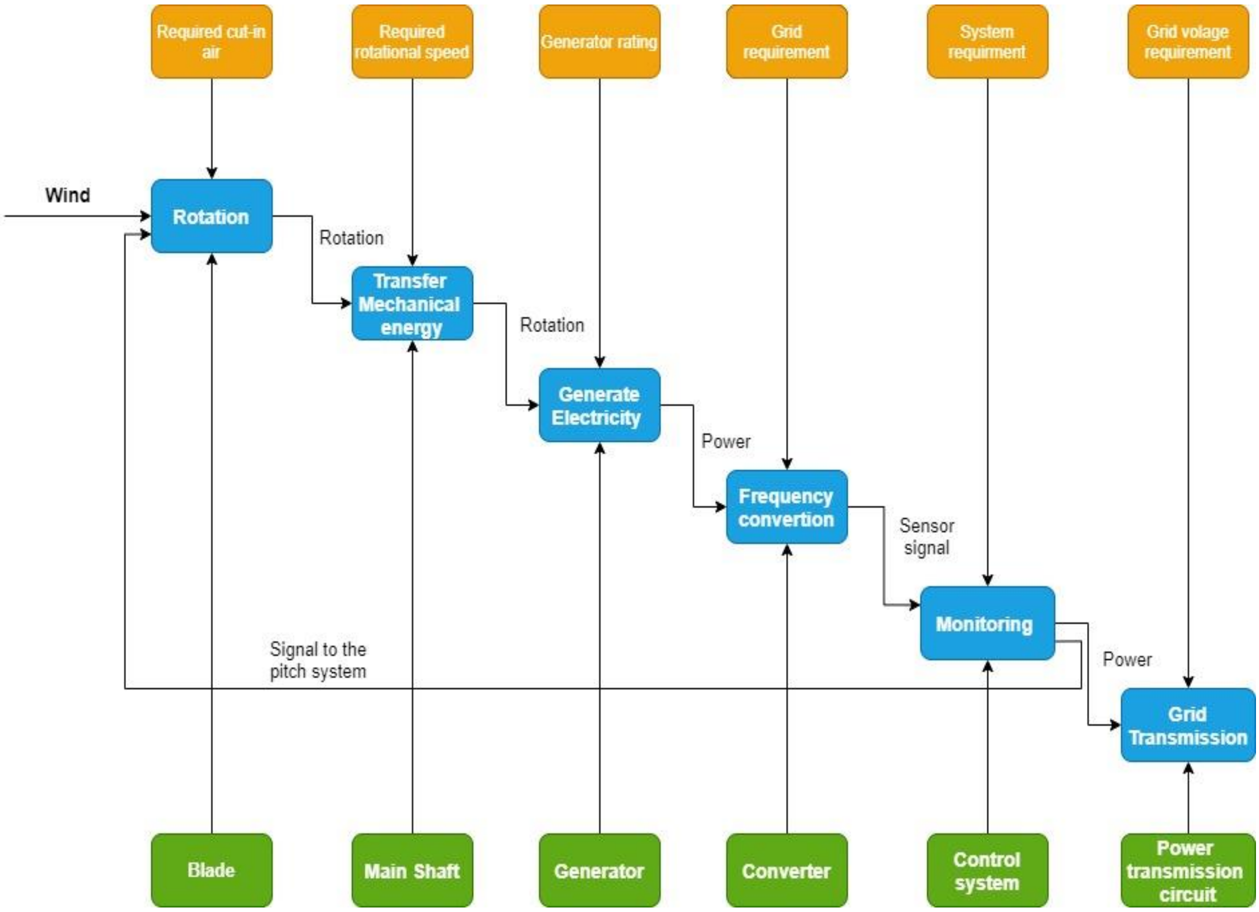


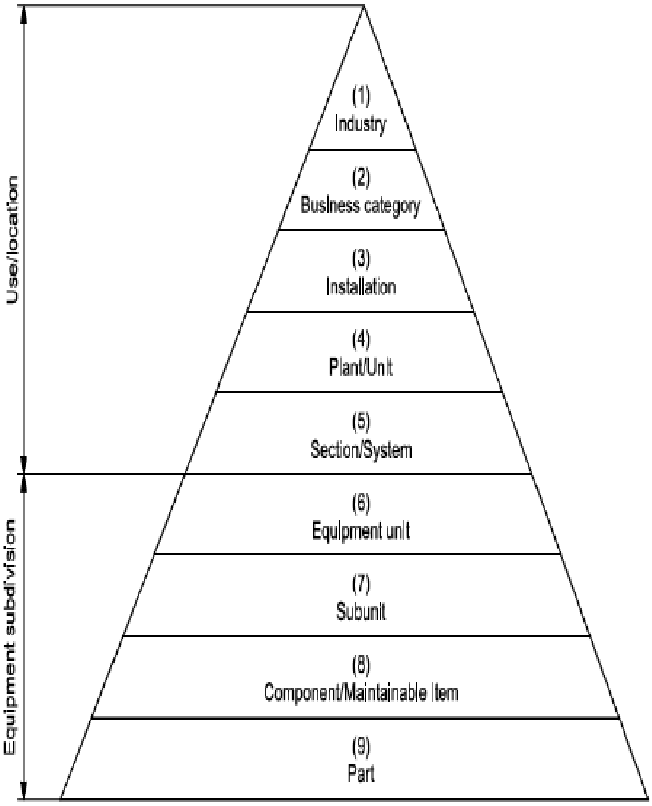
Figure 31. Operating case scenario of the Direct-drive wind turbine system

The Converter is to enable variable frequency conversion from the generator output to make it appropriate for the grid or load. The turbine also has its control system, which is the brain of the turbine; it monitors the performance of the entire system. The control system regulates the pitch system, which enables the angle positioning of the blade for maximum wind capture, while the yaw system for rotation of the turbine heads toward the direction of the wind.

5.2. Technical Hierarchy of the Direct-Drive Wind turbine

The development of the wind turbine taxonomy classification or Technical hierarchy is step 2 in the analysis framework and is based on the systematic classification of the turbine items according to their location.

The taxonomy example used is quite similar to the Relia Wind taxonomy previously mentioned in section 3.6.1.1. Moreover, the Relia wind taxonomy failed to distinguish between the maintainable and non-maintainable components properly. The taxonomy terminology in the Relia wind taxonomy includes System, Sub-system, Assembly, Sub-assembly, and Component. For this research, the ISO 14224 standard given in Figure 32 was adopted because it presents a better terminology and well-detailed definition of the levels in the hierarchy.



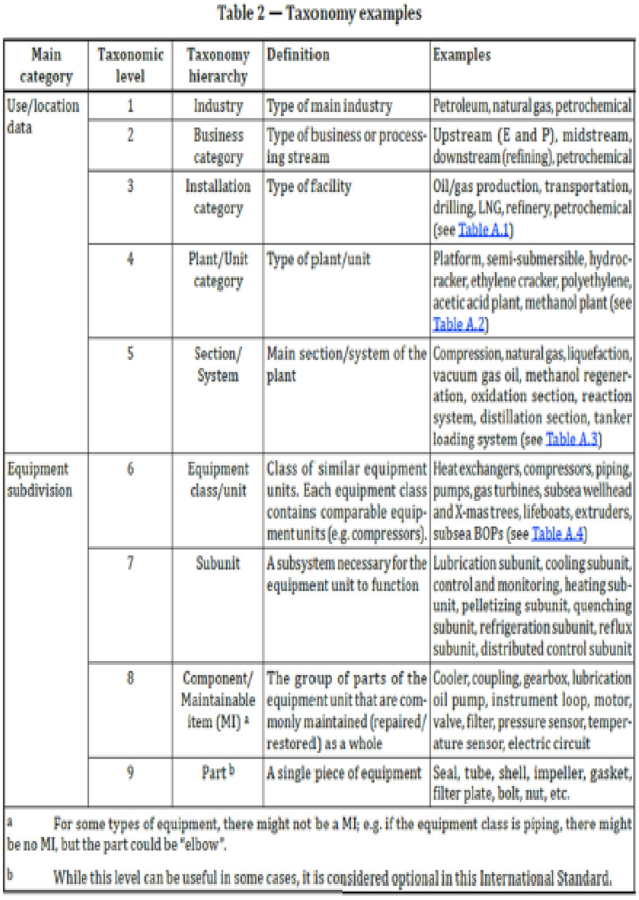


Table 2 — Taxonomy examples

Main category	Taxonomic level	Taxonomy hierarchy	Definition	Examples
Use/location data	1	Industry	Type of main industry	Petroleum, natural gas, petrochemical
	2	Business category	Type of business or processing stream	Upstream (E and P), midstream, downstream (refining), petrochemical
	3	Installation category	Type of facility	Oil/gas production, transportation, drilling, LNG, refinery, petrochemical (see Table A.1)
	4	Plant/Unit category	Type of plant/unit	Platform, semi-submersible, hydrocracker, ethylene cracker, polyethylene, acetic acid plant, methanol plant (see Table A.2)
	5	Section/ System	Main section/system of the plant	Compression, natural gas, liquefaction, vacuum gas oil, methanol regeneration, oxidation section, reaction system, distillation section, tanker loading system (see Table A.3)
Equipment subdivision	6	Equipment class/unit	Class of similar equipment units. Each equipment class contains comparable equipment units (e.g. compressors).	Heat exchangers, compressors, piping, pumps, gas turbines, subsea wellhead and X-mas trees, lifeboats, extruders, subsea BOPs (see Table A.4)
	7	Subunit	A subsystem necessary for the equipment unit to function	Lubrication subunit, cooling subunit, control and monitoring, heating subunit, pelletizing subunit, quenching subunit, refrigeration subunit, reflux subunit, distributed control subunit
	8	Component/ Maintainable item (MI) [a]	The group of parts of the equipment unit that are commonly maintained (repaired/ restored) as a whole	Cooler, coupling, gearbox, lubrication oil pump, instrument loop, motor, valve, filter, pressure sensor, temperature sensor, electric circuit
	9	Part [b]	A single piece of equipment	Seal, tube, shell, impeller, gasket, filter plate, bolt, nut, etc.

[a] For some types of equipment, there might not be a MI; e.g. if the equipment class is piping, there might be no MI, but the part could be "elbow".

[b] While this level can be useful in some cases, it is considered optional in this International Standard.

Figure 32. Taxonomy classification with taxonomy level (ISO-14224, 2016)

The ISO 14224 taxonomy structure comprises nine levels where levels 1 to 5 are related to the High-level industry application while levels 6 to 9 relate to the equipment unit. The collection of reliability and maintenance data is focused on the equipment unit level and the subsequent subunit depending on the complexity of the equipment unit (ISO-14224, 2016). However, the proposed technical hierarchy for the selected system will begin at level 4 (Plant unit), which is the Wind Turbine as a whole. The previous research on wind turbine taxonomy mostly used the Relia wind Consortium terminology mentioned earlier; therefore, it is important to show the similarity between the hierarchy terminology. Table 11 illustrates the similarity of the terminology used in developing the Relia wind Consortium taxonomy and the terminology presented in the ISO 14224 standard.

Table 11. Similarity between the ISO terminology and the Relia wind Consortium Terminology

Hierarchy Terminology		
Relia wind Level	ISO 14224 level	Level
	Industry	1
	Business category	2
	Installation	3
System	Plant /uint	4
Sub-system	Section/System	5
Assembly	Equipment Unit	6
Sub-assembly	Sub-unit	7
Component	Component/Maintainable Item	8
	Part	9

The Technical Hierarchy will focus on level 4 to level 8, including the Plant/unit level, Section/system, Equipment unit, Sub-unit, and the component/maintainable item. It also includes the admin tag and component tag to link each component to its parent equipment. The hierarchy developed was done in a Microsoft Excel worksheet where all items have been classified under different levels based on the ISO 14224 standard. Other literature describing wind turbine taxonomy systems, such as the taxonomy presented by (Kaidis, 2014), was used to compare. Moreover, proper measures were taken to ensure the right maintainable items are tagged.

5.2.1 Technical Hierarchy Development process

The ISO 14224 taxonomy standard is adopted in the hierarchy development process starting from level 4. Firstly, break down the Wind turbine (level 4) into several sections/systems (level 5), for example, the Rotor module, Drive-train module Electrical Module, etc. At each section or system level, the associated equipment unit is defined, and the level in the hierarchy is specified as well, which is level 6. Each section/system can consist of several equipment units depending on the capacity; for example, the Rotor module comprises the Hub, Pitch system, and the three blades. The equipment unit is further broken down into level 7, which is the Sub-unit level; for example, the pitch system consists of the pitch cabinet and pitch drive. This level is also classified as the "*Admin Tag.*" The last level considered is level 8, where the maintainable components are grouped. For instance, the maintenance component in the pitch drive includes a pitch motor, pitch gearbox, air-brake, and position encoder (sensor). These maintainable components are tagged corresponding to the parent tag for easy identification, especially during maintenance. This whole process is repeated for each section/system of the wind turbine, respectively.

Table 12 represents the result of the developed Technical hierarchy for the selected Wind Turbine system. The complete Technical hierarchy excel worksheet can be found in Appendix B.

Table 12. Example of the Wind turbine Technical Hierarchy

Technical Hierarchy of the Direct-drive Wind Turbine (ISO 14224 Standard)							
Taxonomy level	**Plant/Unit**	**Section/System**	**Equipment Unit**	**Subunit**	**Component**	**Admin tag**	**Tag no**
4	**Wind Turbine**						
5		**20- Rotor Module**					20-00-00
6			Rotor Hub				20-10-00
7				Hub		20-10-HB	
6			Pitch system				20-11-00
7				Pitch cabinet		20-11-CB	
8					Battery		20-11-CB-B001
8					Battery charger		20-11-CB-B002
8					Pitch controller		20-11-CB-C001
8					Heater		20-11-CB-H001
7				Pitch drive		20-11-PD	
8					Pitch motor		20-11-PD-M001
8					Pitch Motor Encoder		20-11-PD-M002
8					Pitch gearbox		20-11-PD-G001
8					Air Brake		20-11-PD-A001
8					Position Encoder		20-11-PD-E001
8					Pitch lube pump		20-11-PD-L001
8					Valves		20-11-PD-V001
6			Blade 1				20-12-00
6			Blade 2				20-13-00
6			Blade 3				20-14-00
5		**21-Drive train Module**					21-00-00
6			Generator				21-10-00
7				Rotor		21-10-RT	
7				Stator		21-10-ST	
7				Sensors		21-10-SS	
8					Temperature sensor		21-10-SS-T001
8					Encoder		21-10-SS-E001
8					Wattmeter		21-10-SS-W001
7				Generator Lubrication subunit		21-10-GL	
8					Pump		21-10-GL-P001
8					Pressure sensor		21-10-GL-P002
8					Reservoir		21-10-GL-R001
8					Valves		21-10-GL-V001
7				Generator cooling subunit		21-10-GC	
8					Cooling fan		21-10-GL-C001
8					Filter		21-10-GC-F001
8					Hose		21-10-GC-H001
8					Radiator		21-10-GC-R001
6			Main shaft set				21-11-00
7				Low speed side		21-11-LS	
8					Main bearingTemperature sensor		21-11-LS- M001
7				Sensors		21-11-SS	
8					Low speed side sensor		21-11-SS-S001
6			Brake				21-12-00
8					Brake sensor		21-12-00-B001

5.2.2. Verification and Validation (Technical Hierarchy)

The technical hierarchy created was verified using the ISO 14224 standard as a base to check the traceability of the items at each level to ensure that items were correctly grouped in their proper hierarchy levels. Meetings were also held with the academic supervisor to compare the result with other study groups at the university, who also developed the technical hierarchy. Overall, the observation from the comparison shows a similar grouping of items at the same hierarchy level.

5.3. Functional Hierarchy and consequence classification

The next step is to develop the system's functional hierarchy, which is linked to the technical hierarchy developed in the initial stage. It presents a general overview of how the system is hierarchically built. Here, the Main function and the system equipment's sub-function are identified and classified based on their criticality level. Figure 33 illustrates the synergy between the technical hierarchy and the functional hierarchy.

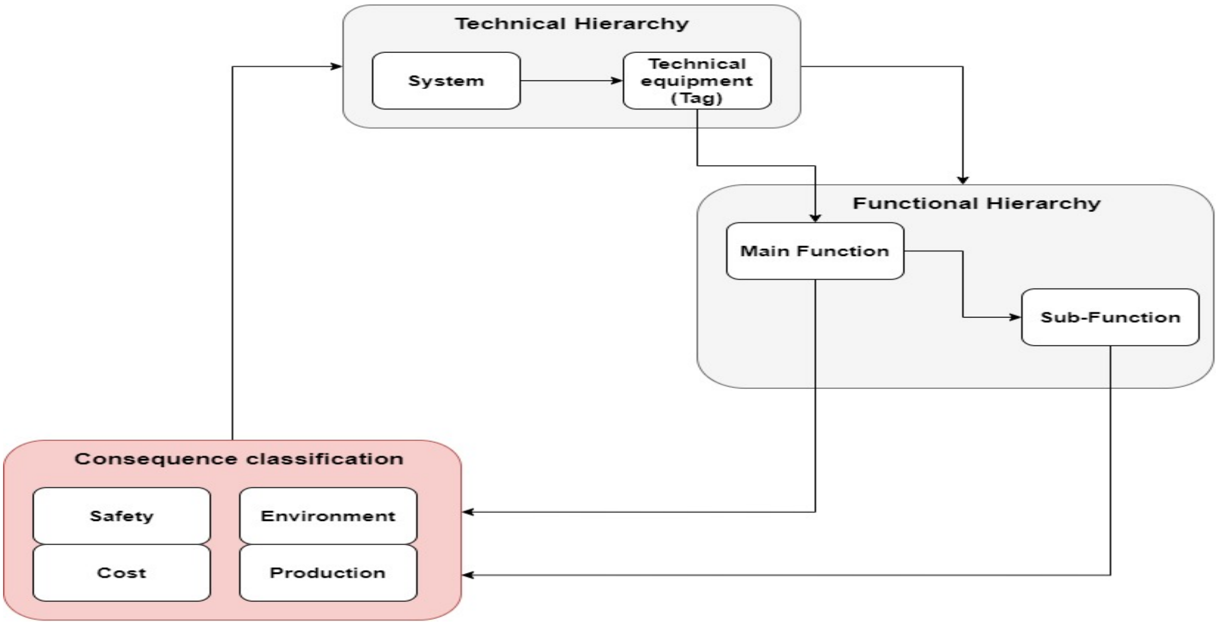


Figure 33. Technical and functional hierarchy interface

The objective is to cover all equipment units and components of the different systems as mentioned in the technical hierarchy with the main function and a supporting sub-function.

Norsok Z-008 standard was adopted for the development of the functional hierarchy. The main function example can be Power generation, distributing, storing, etc. (NORSOK-Z-008, 2001), depending on the equipment. Based on the recommendation from NORSOK- Z -008 Standard, the Main functions were created to fit the wind turbine system. Also, the subfunction used was adopted from the Norsok-Z-008 standard and described in Table 13

Table 13. Main and Sub-function description

Main-function		Sub-Function (NORSOK-Z-008, 2001)	Sub-Function Description
Wind catching		MF	Main Function
Angle positioning		PSV	Pressure relief
Transferring		PSD	Process Shutdown
Generating		ESD	Emergency shutdown
Lubricating		CONTROL	Controlling
Cooling		IND	Local indicator
Braking		ALARM	Monitoring
Frequency converting		EQSD	Shutdown equipment
Monitoring			
Housing			
Turbine Head rotating			
Transmitting			
Supporting			

5.3.1 Functional Hierarchy Development process

The system’s main functions are defined in a separate Microsoft Excel worksheet. Recall that different sections/systems and equipment units were specified in the technical hierarchy. Here, the goal is to state the main function of each of the equipment units in the system. For example, the rotor module system has the pitch system and blade; therefore, the system's main function is stated as Wind catching and Angle positioning. This means that the blade does the wind-catching function while the pitch system does the angle positioning function. Another example is the electrical module which has a frequency converter and control system. Therefore, the main function is converting and monitoring. This means that converting is done by the frequency converter while the control system does the monitoring function.

After each main function of the various systems has been identified, the next step is to determine the sub-functions of each main function. Each system would have a sub-function called “MAIN,” which constitutes the main function. Note that each component must be attached to only one sub-function, depending on the functionality. A sub-function can include many components; therefore, the subfunction should be a general subfunction that can be related to several components in that particular system. For example, the rotor module has the main function called angle positioning; the sub-functions would be MAIN, ALARM, CONTROL, IND. The component that can be related to the CONTROL sub-function includes the pitch motor and airbrake. The component that performs the ALARM sub-function includes the position encoder, sensors, transmitters. These steps must be completed for all the systems to enable consequence assessment.

The functional hierarchy created specified only the main function and sub-function in the excel worksheet; the component is not specified. If hierarchy were to be implemented into a database, it would be linked to the technical hierarchy with the connection between functions and components (Figure 33 illustrates this integration). Table 14 represents the result of the developed Functional hierarchy and consequence classification of the Direct-drive Wind Turbine system. The complete excel sheet can be found in Appendix C

Table 14. Example of the Wind turbine functional Hierarchy

Functional Hierarchy of the Offshore wind turbine

Main system	System/Section	Main function (MF)	Sub-function	Function Description	Consequence classification					Criticality
					Safety	Environment	Repair cost	Production	Frequency	
Wind Turbine										
	Rotor Module									
		Wind catching		Harversting wind by the blade	6	6	4	3	4	H
			MAIN		MF	MF	MF	MF	MF	H
		Angle positioning		Action done by the pitch system	6	6	5	5	4	M
			MAIN	Main task	MF	MF	MF	MF	MF	M
			ALARM	Monitoring	6	6	6	5	4	M
			CONTROL	Regulating the pitch rotation	MF	MF	MF	MF	MF	M
			IND	Local Indicator	6	6	6	5	3	M
	Drive train Module									
		Transfering		Transfer mechanical energy to the generator	6	6	4	3	3	H
			MAIN	Transfering	MF	MF	MF	MF	MF	H
			ALARM	Monitoring	6	6	5	6	3	L
		Generating		Produce electricity	6	6	3	3	4	H
			MAIN	Generating power	MF	MF	MF	MF	MF	H
			ESD	Emergency shutdown	6	6	4	MF	2	M
			ALARM	Monitoring	6	6	5	5	3	M
			IND	Local Indicator	6	6	5	6	3	M
		Lubricating		Lubricating the generator	6	6	4	4	3	M
			MAIN	Main task	MF	MF	MF	MF	MF	M
			PSV	Safety equipment for pressure relief	6	6	4	4	3	M
			ALARM	Monitoring	6	6	5	6	3	M
			CONTROL	Regulating	MF	MF	MF	MF	MF	M
			PSD	Process shutdown	6	6	4	4	3	M
		Cooling		cooling the generator	6	6	4	4	3	M
			MAIN	cooling	MF	MF	MF	MF	MF	M
			CONTROL	Regulating	MF	MF	MF	MF	MF	M
		Braking		Speed reduction	6	6	4	3	4	H
			MAIN		MF	MF	MF	MF	MF	H
			ESD	Emergency shutdown	6	6	4	4	3	M
			CONTROL	Regulating	MF	MF	MF	MF	MF	H

5.3.2 Consequence Classification

The consequence classification will help determine the critical functions. The criticality analysis is established for all the main functions and sub-function defined in the functional hierarchy and ranked based on the consequence of safety, environment, production, and repair cost. It can be High, Medium, or Low criticality. However, some sub-function will inherit the consequence class as the main function, while others will have a predefined consequence class that is not dependent on the main function. For example, the CONTROL sub-function always inherits the consequence class of the main function (MF) (NORSOK-Z-008, 2001).

Evaluating the main function is either according to Total loss of function or Incorrect function. A combination of the failure frequency and the highest consequence class among safety, environment, production, and repair cost parameters gives the criticality leve4.

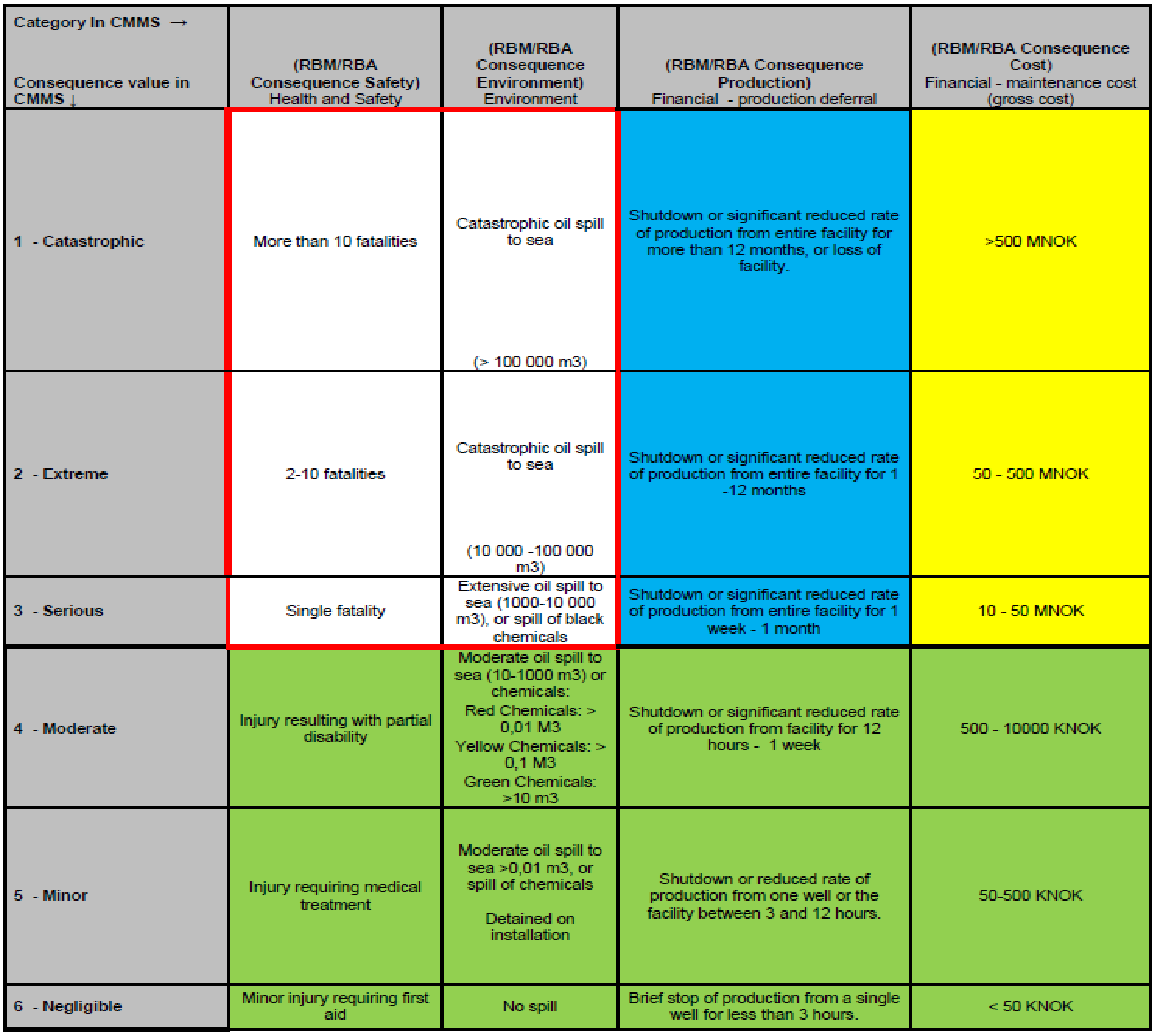
5.3.3. Process of consequence classification

As illustrated in Table 14, the consequence class of each main and sub-function has been assigned. The NORSOK -Z-008 standard is the basis for the classification, and the failure mode considered is "Total loss of function."

The process aims to determine how the total loss of function will affect the system and assign the criticality number 1-6 (catastrophic - negligible) following the risk decision criteria shown in table 15. The risk decision criteria used was obtained from the case company (Aker solutions). Next, the frequency class in Table 16 is used to estimate the failure frequency of the functions, and it is based on the expected failure rate obtained from the reference report "*failure rate, repair time and unscheduled O&M cost analysis of offshore wind turbines*" by (Carroll et al., 2016). Finally, after assigning the frequency class, the risk matrix given in Table 17 is used to determine the overall criticality level. Here, the frequency and consequence described earlier are combined.

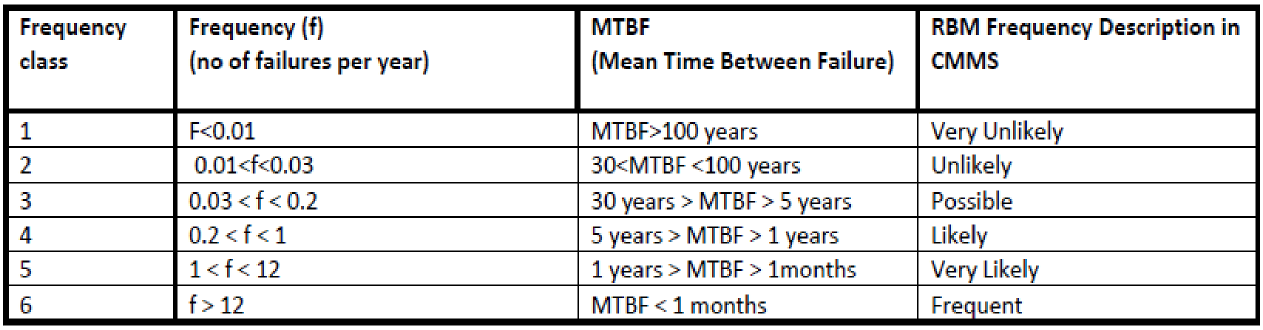
It implies that the highest consequence of the main or sub-function is combined with the frequency class to determine the criticality

Table 15. Risk decision criteria (AkerBP, 2020)



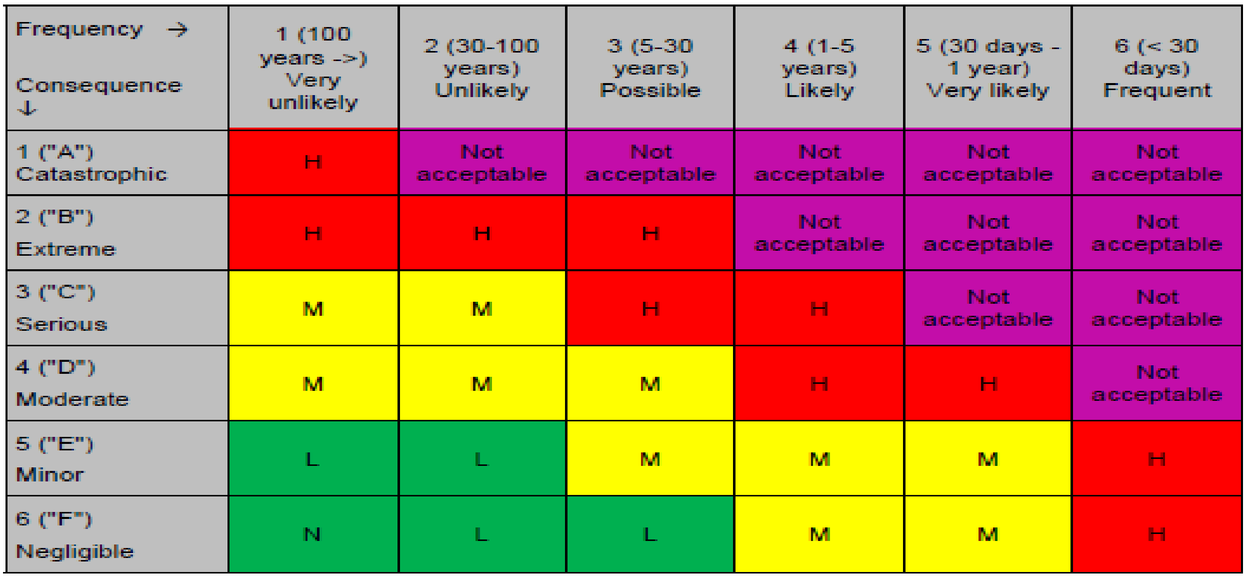
Category In CMMS → Consequence value in CMMS ↓	(RBM/RBA Consequence Safety) Health and Safety	(RBM/RBA Consequence Environment) Environment	(RBM/RBA Consequence Production) Financial - production deferral	(RBM/RBA Consequence Cost) Financial - maintenance cost (gross cost)
1 - Catastrophic	More than 10 fatalities	Catastrophic oil spill to sea (> 100 000 m3)	Shutdown or significant reduced rate of production from entire facility for more than 12 months, or loss of facility.	>500 MNOK
2 - Extreme	2-10 fatalities	Catastrophic oil spill to sea (10 000 -100 000 m3)	Shutdown or significant reduced rate of production from entire facility for 1 -12 months	50 - 500 MNOK
3 - Serious	Single fatality	Extensive oil spill to sea (1000-10 000 m3), or spill of black chemicals	Shutdown or significant reduced rate of production from entire facility for 1 week - 1 month	10 - 50 MNOK
4 - Moderate	Injury resulting with partial disability	Moderate oil spill to sea (10-1000 m3) or chemicals: Red Chemicals: > 0,01 M3 Yellow Chemicals: > 0,1 M3 Green Chemicals: >10 m3	Shutdown or significant reduced rate of production from facility for 12 hours - 1 week	500 - 10000 KNOK
5 - Minor	Injury requiring medical treatment	Moderate oil spill to sea >0,01 m3, or spill of chemicals Detained on installation	Shutdown or reduced rate of production from one well or the facility between 3 and 12 hours.	50-500 KNOK
6 - Negligible	Minor injury requiring first aid	No spill	Brief stop of production from a single well for less than 3 hours.	< 50 KNOK

Table 16. Frequency table (AkerBP, 2020)



Frequency class	Frequency (f) (no of failures per year)	MTBF (Mean Time Between Failure)	RBM Frequency Description in CMMS
1	F<0.01	MTBF>100 years	Very Unlikely
2	0.01<f<0.03	30<MTBF <100 years	Unlikely
3	0.03 < f < 0.2	30 years > MTBF > 5 years	Possible
4	0.2 < f < 1	5 years > MTBF > 1 years	Likely
5	1 < f < 12	1 years > MTBF > 1months	Very Likely
6	f > 12	MTBF < 1 months	Frequent

Table 17. Risk criticality matrix (AkerBP, 2020)



Frequency → Consequence ↓	1 (100 years ->) Very unlikely	2 (30-100 years) Unlikely	3 (5-30 years) Possible	4 (1-5 years) Likely	5 (30 days - 1 year) Very likely	6 (< 30 days) Frequent
1 ("A") Catastrophic	H	Not acceptable	Not acceptable	Not acceptable	Not acceptable	Not acceptable
2 ("B") Extreme	H	H	H	Not acceptable	Not acceptable	Not acceptable
3 ("C") Serious	M	M	H	H	Not acceptable	Not acceptable
4 ("D") Moderate	M	M	M	H	H	Not acceptable
5 ("E") Minor	L	L	M	M	M	H
6 ("F") Negligible	N	L	L	M	M	H

The risk decision criteria used are shown in table 15 and were obtained from the case company (Aker solution). Although it is related to the oil and gas sector, reasonable assumptions were made based on engineering judgment and background knowledge from the report presented by Carroll et al. (2016). In the oil and gas sector, safety and environmental factors are highly prioritized because equipment failure can be very hazardous as well as a huge financial consequence. Cases such as oil spills and fire disasters can lead to serious accidents and damage to the environment. In contrast, it is mostly minor or negligible for the offshore wind industry since the failure function of the wind turbine components does not lead to fatality or pollution to the environment.

For example, if the main function (MF) “Angle positioning” fails, a consequence value would be assigned to safety, environment, repair cost, and production. The same applies to the sub-function under the Angle positioning such as the ALARM, CONTROL, & IND. The CONTROL sub-function includes all components within the main function borders; therefore, it inherits the MF consequence class. This has been specified in the example in Table 14. Furthermore, insight into repair costs was taken from relevant literature. The most complete dataset regarding reliability and maintainability was published by Carroll et al. (2016).

For example:

Table 18 illustrates a brief example of how the classification is done. One of the main functions of the rotor module is the “Angle positioning.” In order to classify this function, the risk decision criteria shown in table 15 is used to assign values to the consequence parameters (safety, environment, repair cost, and production). Although the risk decision criteria used is related to the oil and gas sector, reasonable assumptions were made based on engineering judgment and background knowledge from the report presented by Carroll et al. (2016). Safety and environmental factors are highly prioritized in the oil and gas sector because equipment failure can be very hazardous and have huge financial consequences. Cases such as oil spills and fire disasters can lead to severe accidents and damage to the environment.

In contrast, base on the description in the risk decision criteria, safety and environmental factor might be negligible for the offshore wind industry. This is because function failure of the wind turbine equipment does not necessarily lead to environmental pollution or serious accident because there is nobody present. For this reason, the value 6 is assigned to safety and environment parameters. Base on reference suggestion, the repair cost for the failure function "Angle positioning" falls between NOK50 -NOK500k; therefore, the value 5 is assigned to the repair cost parameter. However, if the Angle positioning function fails, it can be classified as a minor failure because it does not lead to shutting down the wind turbine. Instead, it can reduce electricity production. For this reason, 5 (minor) is assigned to the production parameter using table 15.

The dataset presented by (Carroll et al., 2016) was used to estimate the failure frequency. Following the frequency class in table 16, class 4 is assigned to this function, which implies that the function failure is likely to occur between 1 to 5 years. Furthermore, the highest parameter value (*among safety, environment, repair cost, production*) for the "Angle positioning" is 5, and the frequency class is 4. Using the risk criticality matrix in table 17, the combination of 5 and 4 will give a ***Medium criticality level.*** This procedure is repeated for the function "ALARM" sub-function and for all main functions and the sub-function defined in the functional hierarchy. Note that the sub-function "MAIN" constitutes the Main function (MF).

Therefore "MF" is indicated in all parameters (safety, environment, cost, and production) because it will inherit the Main function class. More examples can be seen in Table 14. The full excel worksheet can be found in Appendix C.

Table 18. Example of the criticality analysis

Main function	Sub-function	Consequence classification				Frequency	Criticality
		Safety	Environment	Repair cost	Production		
Angle positioning		6	6	5	5	4	M
	MAIN	MF	MF	MF	MF	MF	M
	ALARM	6	6	6	5	4	M

In conclusion, the result from the functional hierarchy and consequence classification presented in table 14 clearly shows the function of the system equipment that is low, medium, and high critical. The function associated with the drive train and electrical module is highly critical. Moreover, a Run-to-failure maintenance strategy is usually assigned to Low critical equipment. At the same time, further analysis may be required for high or medium critical equipment to determine the most effective maintenance strategy. In this case, the failure mode and effect analysis (FMEA) will be used. Also, this process was verified and validated by experts from Aker solution, and the NORSOK-Z-008 standard was used to assess the criticality analysis.

5.3.4. Verification and Validation (Functional hierarchy & Consequence classification)

After developing the functional hierarchy and consequence classification, a meeting was held with both the academic and case company supervisor to verify the procedure and input values used. The major concern was the inputs of the consequence classification due to the risk decision criteria used. As mention earlier, the risk decision criteria used in the process are related to the oil and gas; therefore, proper classification with the correct risk criteria is required for validation. A discussion section was also held with the academic supervisor to compare the result with other study groups at the university. The result is similar because they also encountered the same issue with the risk decision criteria. However, the main function and sub-function used were similar because they also adopted the Norsok-Z-008 standard.

5.4. Failure Mode and Root cause Analysis

The next step presented in the analysis workflow in figure 30 is the failure mode and effect analysis (FMEA). The FMEA has been described in an earlier section 3.11 as a qualitative tool used to identify the possible failure mode, the effect of the failure mode, and the root cause of the failure in a system. Technically, the FMEA focuses mostly on the root cause of failure, especially for high critical components. Therefore, this analysis will only focus on the system components that have high and medium criticality in the consequence classification done in section 5.3.3.

5.4.1. FMEA layout

There are several standard layouts for the FMEA process, the MIL-STD -1629A (1980) is widely used and was developed by the US Department of Defense (DOD, 1980). The FMEA process was carried out in a Microsoft Excel worksheet, and the content is described as follows:

Equipment unit:

The section/system of the wind turbine is listed out, and the equipment unit belonging to that section is also identified. The equipment to be analyzed are those with high and medium criticality in the consequence classification. The blade generator, for example, has a high criticality; therefore, it has been selected for the FMEA process

Main Function:

The FMEA also presents a brief explanation of the function of each piece of equipment that has been selected.

Potential failure mode:

The failure mode aims to describe how or in what way can the function of the component fails. Note that the failure mode is not the cause of failure, but the root cause probability can be related to the failure mode. Many research works have identified different failure modes for wind turbine components using generic terms like electrical failure, mechanical failure, etc. However, this failure is can instead be described as the failure mechanism. For this purpose, the ISO 14224 standard was used to adopt the different failure modes that apply to the components of the wind turbine system. This failure mode is also being classified according to its possible failure mechanism, as shown in table *19*.

Table 19. Failure Mode Description (ISO-14224, 2016)

Failure Mode			
Failure Mechanism	**Failure mode**	**Failure mode description**	**Examples**
Instrument failure	AIR	Abnormal instrument reading	False alarm, faulty instrument indication
Material failure	BRD	Breakdown	Serious damage (seizure, breakage)
Electrical failure	DOP	Delayed operation	Delayed command response
Mechanical failure	FRO	Failure to rotate	Failure to rotate
Mechanical failure	FTF	Failure to function on demand	It doesn't start on demand, failure to respond to signal
Electrical failure	FTI	Failure to function as intended	Response not as expected (circuit breaker)
Electrical failure	FTR	Failure to Regulate	Poor response to feedback/ fails to control
Electrical failure	LOO	low output	Outpower below acceptance
Mechanical failure	NOI	Noise	Abnormal noise/sound
Thermal failure	OHE	Overheating	Machine parts, cables / high internal temperature
Instrument failure	PDE	Parameter deviation	Monitored parameter exceeding limits
Electrical failure	POW	Insufficient power	lack or too low supply of power
Material failure	STD	Structure deficiency	Material damage (Cracks, wear, corrosion)
Electrical failure	UST	Spurious stop	Unexpected shutdown
Mechanical failure	VIB	Vibration	Abnormal/ Excess vibration

Local failure effect:

The local effect can be said to be the impact of the function failure on the system. It can also be classified in the same way as the cause of failure. Each failure mode identified in the excel worksheet has a defined local effect on the system.

Global failure effect:

This is the same as the local failure effect. However, it considered the effect on the system and the entire process, windfarm, services, customers, and regulations.

Root cause:

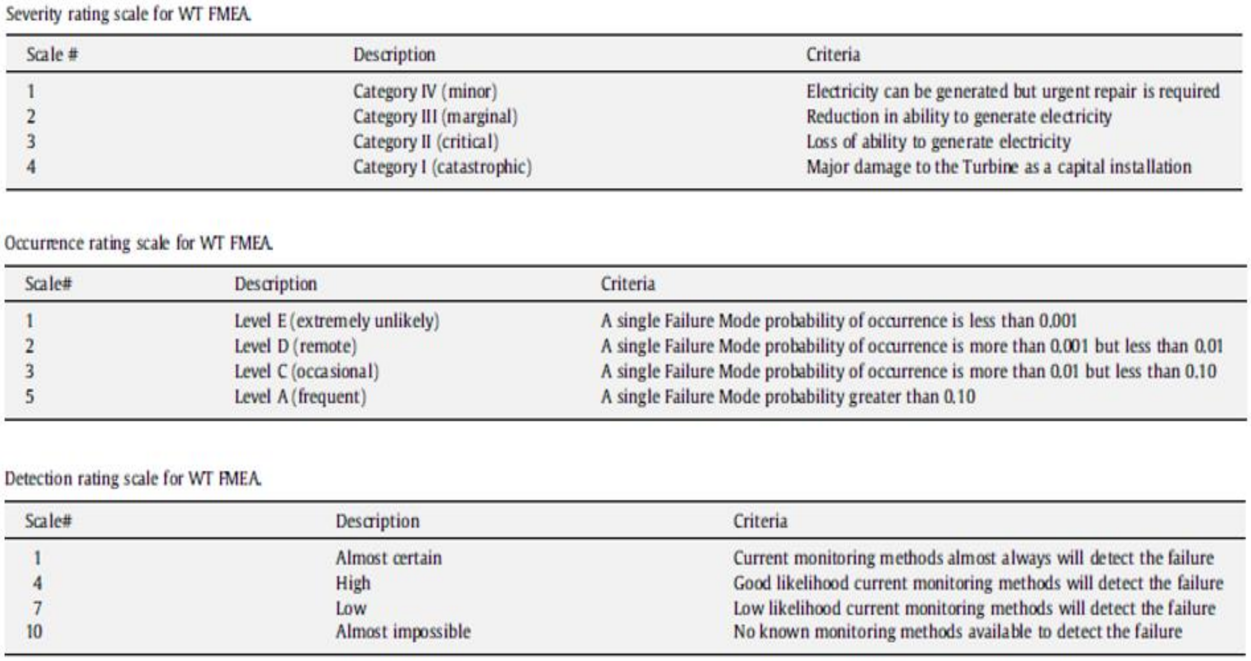
The root cause of failure describes the actual cause or the mechanism that leads the function to fail. It might be corrosion, cracks, material failure, leakages, etc.

Severity, Occurrence, and Detection:

Severity is used to rank the magnitude of the failure effect on the system. The occurrence defines how often or how frequently the root cause of failure is likely to occur, while the Detection can be defined as how well the cause of failure can be identified (Tavner, 2012).

Depending on the standard of FMEA adopted, a numeric scale ranging from 1 to 10 is used to rate the severity, occurrence, and detection factors. However, Arabian-Hoseynabadi et al. (2010) presented a modified scale rating for FMEA methodology, as shown in Table 20. This improvement claims to makes the FMEA methodology more practical for wind turbine systems (Shafiee & Dinmohammadi, 2014). Any standard implored must be used through the FMEA. Therefore, the proposed FMEA will follow the rating scale below

Table 20. Severity, Occurrence, and Detection rating (Arabian-Hoseynabadi et al., 2010)



Severity rating scale for WT FMEA.

Scale #	Description	Criteria
1	Category IV (minor)	Electricity can be generated but urgent repair is required
2	Category III (marginal)	Reduction in ability to generate electricity
3	Category II (critical)	Loss of ability to generate electricity
4	Category I (catastrophic)	Major damage to the Turbine as a capital installation

Occurrence rating scale for WT FMEA.

Scale#	Description	Criteria
1	Level E (extremely unlikely)	A single Failure Mode probability of occurrence is less than 0.001
2	Level D (remote)	A single Failure Mode probability of occurrence is more than 0.001 but less than 0.01
3	Level C (occasional)	A single Failure Mode probability of occurrence is more than 0.01 but less than 0.10
5	Level A (frequent)	A single Failure Mode probability greater than 0.10

Detection rating scale for WT FMEA.

Scale#	Description	Criteria
1	Almost certain	Current monitoring methods almost always will detect the failure
4	High	Good likelihood current monitoring methods will detect the failure
7	Low	Low likelihood current monitoring methods will detect the failure
10	Almost impossible	No known monitoring methods available to detect the failure

Risk priority number (RPN):

The risk priority number can be used to analyze the system base of the failure mode with a high *RPN* number. This s is obtained by multiplying

Severity * Occurrence * Detection = RPN.

For example

As illustrated in table 21, one failure of the Generator has been identified as OHE (overheating), the effect of OHE is defined as “damage to the generator component,” and the root cause of OHE can be insufficient cooling or Electrical fault. Therefore, using the rating scale presented in Table 20, level 4 is assigned the severity of the effect of OHE. This is because the OHE of the generator can damage the generator and can even lead to a fire. Also, consider that the generator is very expensive; therefore, generator damage can be catastrophic. Base on the suggestion from (Shafiee & Dinmohammadi, 2014), the value 5 is assigned to the occurrence, which means that OHE happens frequently.

Moreover, the generator is well equipped with a temperature sensor, which means that there is a high possibility of detecting this failure. For this reason, the value 4 is assigned to the detection parameter. Multiplying these three parameters gives the RPN as 80. This procedure is repeated for all the equipment listed in Table 21.

Table 21. Example of the FMEA worksheet

Failure Mode Effects Analysis (FMEA)

OWNER: Udoh Francis Makua

FMEA Workshop
Wind Turbine system(Direct Drive)

Date:
Year: 2021

Wind Turbine system/section	Equipment unit	Main Funcition	Potential Failure Mode	Local Failure effect	Global failure effect	Severity (S)	Potential Root cause	occurrence (O)	Current Controls	Detection (D)	RPN	Recommended action	Action taken	SEV	OCC	DET	RPN
What system is to Investigated	What are the Equipment in the sytem	What is the Function of the Equipment.	In what way can the function fail	What is the impact of the function failure on the system	What is the impact of the function failure on the system, process, costomer and regulation	How severe is the effect	What causes the function to fail	How frequent does the Failure mode occur	What are the existing controls/ procedures to prevent the failure mode the root cause	How possible can the cause or failure be detected	Risk priority number (Given by S*O*D)	What can be done to reduce failure and increase detetion	What are the action taken				
Rotor Module																	
	Pitch system	The rotor pitch system is generally located inside the rotor hub. The pitch is helps in angle positioning of the blade toward the wind for effective energy catching	**FTR**	Uncontrolled blade pitching	Lost of efficiency of the turbine	3	Controller failure/malfunction, wearing of pitch gear	3	Coprehensive inspection operation and maintenance proceudre should be strictly adhere to. Comprehensive inspection inspection procedure. New Design specification for the components.	4	36			3	3	4	36
			STD	Unable to to operate properly due wearing of the gears	Lost efficiency	3	Material fatique, Corrosion and cracks and insuficient lubrication	3		7	63			2	3	7	63
			OHE	Deterioration/damage to the pitch controller	Loss of efficiency	3	Electrical overload/ insulation failure	3		7	63			2	3	7	63
			AIR	low or too high wind capture	Lost efficiency	3	Fabrication error/ sensor failure	3		4	36			2	3	4	36
	Blade	The blades are attached to the rotor hub. The function of the blade is for wind catching to enable the whole process	**VIB**	Increase d mechanical load	Lost of efficiency	3	High wind speed and delamination	3		4	36			2	3	4	36
			FRO	loss of energy production	Shutdown of the single turbine	3	Mechanical wear of the blade root couplings	3		4	36			3	3	4	36
			STD	Unable to capture enough wind	Reduced total power production	4	Material fatique, Corrosion and cracks	3		4	48			2	3	4	48
Drive-Train Module																	
	Main shaft	For the Direct-drive wind turbine, the main shaft is located between the rotor and the generator and it is been supported by the main bearing. It is responsible for transfering mechanical energy from	**STD**	Increased fatigue and vibration to attached system components	lost efficiency of the turbine	3	Material fatique	3	The maintenance procedure contained in the manual or as specified by the OEM should be strictly adhere to. Comprehensive inspection inspection procedure. Design modification for the component	7	63			2	3	7	63
			VIB	Increased machnical load for the connected components	lost efficiency/ full stop single turbine	2	Insufficient material quality	3		7	42			2	3	7	42
	Mechnical Brake	The brake system is connetec to the shaft in order to reduce the rotational speed during high speed condition or during emergcy shut-down of the system	**STD**	Increased fatigue and vibration to attached system components	Lost efficiency	3	Mechanical wear	3		7	63			2	3	7	63
			BRD	Damage to other component due to uncontrolled rotational speed	Full stop single wind turbine	4	Design fault/ Aging material	2		7	56			3	2	7	56
			FTF	Damage to the generator due to overloading	Full stop single wind turbine	4	Control Failure	2		7	56			3	2	7	56
	Generator	The generator is the power equipment in the turbine. It converts the mechanical energy from the shaft to electrical energy. For the Direct-drive turbine, the generator has several permanent magnet which aid to achieve the desire output voltage	**LOO**	Inadeqaute power production	Unable to integrate with the grid	3	Electrical overload/ Winding failure	3		4	36			2	3	4	36
			STD	Increased fatigue and vibration to attached system components	Lost efficiency	3	Material wear	4		7	84			2	4	7	84
			NOI	Noise pollution / increased compoent degreadation	Noise pollution	3	Loosen parts	3		4	36			2	3	4	36
			BRD	Unable to generate power	Loss of power generation single turbine	4	Material defect	3		7	84			3	3	7	84
			OHE	Damage to the generator component	Full stop single turbine	4	Electrial overload/ insufficient cooling	5		4	80			3	5	4	80

The FMEA presented in Table 21 illustrates the different failure modes of selected equipment in the system. The full worksheet can be found in Appendix D. In addition, the failure root cause, effects on the system, and the RPN has been determined and the equipment in the drive train have a higher RPN. The data used for the rank of the RPN was primarily based on available literature discussed in section 3.6.1.3. Though not all failure modes and root causes were covered, some reasonable assumptions were made to cover all parameters. Identifying the different failure modes makes it easier to develop a maintenance program and define the appropriate maintenance task for each failure. This process will be discussed in section 5.5.

5.5. Maintenance task selection and Manning study

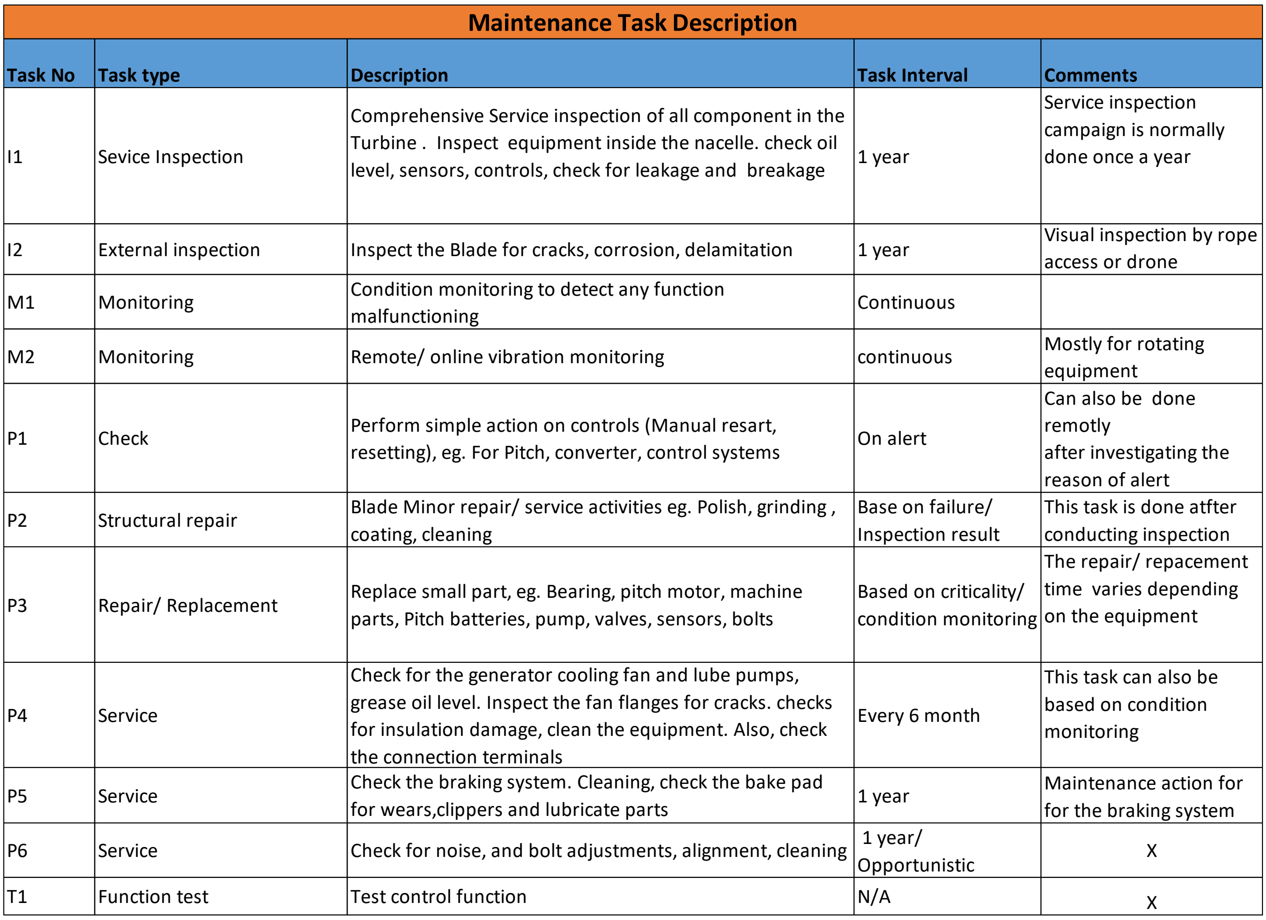
The maintenance operation is essential for offshore wind turbine systems to ensure continuous reliability and availability improvement. Maintenance task selection is a necessary decision-making process used for adequate planning of maintenance operations. In the earlier section of the analysis, we have successfully identified the critical component of the system, and the different failure modes and root causes have been defined. This section will present the planned maintenance interval and activities for the different critical failure modes of the system equipment. Corrective maintenance is carrying out on components with low criticality; therefore, the focus will be on developing the planned maintenance activities.

There are different maintenance actions assigned to the components of the WT depending on the failure mode. Decision logic is used as a guide throughout the process. Section 3.6.1.4 of this report presented an example of decision logic for selecting maintenance strategy, while section 3.4.2 described different maintenance actions, including repair, improvement, inspection, and service. However, the information used to develop the maintenance task was based on the answer obtained from the interview conducted for this research and references online.

5.5.1. Planned Maintenance Task

Table 22 below illustrates the planned maintenance activities for some wind turbine (WT) components. Here, the task type, task number, task interval, and the description of the maintenance action are presented in the table. Due to limited information, the focus was mainly on equipment in the rotor module and the drive train. The maintenance task covers only the failure mode with a high-risk priority number (RPN) in the FMEA.

Table 22. Maintenance activities



Maintenance Task Description

Task No	Task type	Description	Task Interval	Comments
I1	Sevice Inspection	Comprehensive Service inspection of all component in the Turbine . Inspect equipment inside the nacelle. check oil level, sensors, controls, check for leakage and breakage	1 year	Service inspection campaign is normally done once a year
I2	External inspection	Inspect the Blade for cracks, corrosion, delamitation	1 year	Visual inspection by rope access or drone
M1	Monitoring	Condition monitoring to detect any function malfunctioning	Continuous	
M2	Monitoring	Remote/ online vibration monitoring	continuous	Mostly for rotating equipment
P1	Check	Perform simple action on controls (Manual resart, resetting), eg. For Pitch, converter, control systems	On alert	Can also be done remotly after investigating the reason of alert
P2	Structural repair	Blade Minor repair/ service activities eg. Polish, grinding , coating, cleaning	Base on failure/ Inspection result	This task is done atfter conducting inspection
P3	Repair/ Replacement	Replace small part, eg. Bearing, pitch motor, machine parts, Pitch batteries, pump, valves, sensors, bolts	Based on criticality/ condition monitoring	The repair/ repacement time varies depending on the equipment
P4	Service	Check for the generator cooling fan and lube pumps, grease oil level. Inspect the fan flanges for cracks. checks for insulation damage, clean the equipment. Also, check the connection terminals	Every 6 month	This task can also be based on condition monitoring
P5	Service	Check the braking system. Cleaning, check the bake pad for wears,clippers and lubricate parts	1 year	Maintenance action for for the braking system
P6	Service	Check for noise, and bolt adjustments, alignment, cleaning	1 year/ Opportunistic	X
T1	Function test	Test control function	N/A	X

Table 23 presents the excel worksheet, which shows how each maintenance activity described in Table 22 is assigned to the failure mode. It can be seen that some failure mode has more than one maintenance activities carried out throughout the lifespan of the equipment. The maintenance time and the number of technicians required are also defined. Some maintenance activities can be done remotely, such as monitoring (M1, M2), and do not need to visit the wind farm or shut down the WT.

Table 23. Baseline Maintenance concept

Baseline Maintenanace Concept (Preventive maintenance) Offshore Wind Turbine system (Direct Drive)							
Wind Turbine system/section	**Equipment unit**	**Function failure**	**Potential Failure Mode**	**Task No.**	**No. of Person**	**Estimated PM Hours**	**Discipline**
Which system in the wind turbine is to be Investigated	What are the Equipment in your sytem	What is the actual functions that failed	In what way can the function fail	What is the number assigned to the task	How many Technicians are needed for the job	What Is the duration of the Maintenance task take	What is the department responsible for the task
Rotor Module							
	Pitch ystem	**Fail to regulate / fail to position the blade towards the of wind direction for energy capture**	**FTR**	**M1**	**N/A**	**N/A**	**Electrical**
				P1	**3**	**5**	**Electrical**
				T1	**2**	**N/A**	**Electrical**
				P3	**3**	**12**	**Mechanical**
			STD	**I1**	**3**	**6**	**Mechanical**
				M1	**N/A**	**N/A**	**Mechanical**
			OHE	**P1**	**3**	**5**	**Mechanical**
	Blade	**Fail to rotate / covert energy from the wind to enable power production**	**VIB**	**M2**	**N/A**	**N/A**	**N/A**
				P2	**4**	**12**	**Mechnical**
				I2	**3**	**4**	**Mechnical**
				P6	**3**	**9**	**Mechnical**
			STD	**I2**	**3**	**4**	**Mechnical**
				P2	**4**	**12**	**Mechnical**
Drive-Train Module							
	Main shaft	**inadequate / fail to tranfer the rotational mechanical energy to the generator**	**STD**	**I1**	**3**	**6**	**Mechanical**
				P6	**3**	**8**	**Mechanical**
			VIB	**M2**	**N/A**	**N/A**	**N/A**
				P6	**3**	**5**	**Mechanical**
	Mechnical Brake	**Fail to reduce the rotational speed or fail to stop the turbine system during emergency**	**STD**	**I1**	**3**	**6**	**Mechanical**
				M1	**N/A**	**N/A**	**N/A**
			FTF	**P5**	**3**	**12**	**Mechanical**
				M1	**N/A**	**N/A**	**N/A**
	Generator	**Fail to convert the rotational mechanical energy to electrical energy**	**STD**	**I1**	**3**	**6**	**Mechanical**
				P6	**3**	**6**	**Mechanical**
				M2	**N/A**	**N/A**	**N/A**
				P3	**3**	**12**	**Mechanical**
			BRD	**M1**	**N/A**	**N/A**	**N/A**
				I1	**3**	**6**	**Mechanical**
			OHE	**P4**	**3**	**8**	**Mechanical**
				M1	**N/A**	**N/A**	**N/A**

5.5.2. Maintenance Timeline

The information from the maintenance concept in Table 23 is simulated using the Anylogic software to visualize each equipment maintenance activity. The system dynamic library was used, and the flow inputs are described in Table 24. In simulating the maintenance operation, the average lifespan of the wind turbine (WT) of 20 years was used (DeepResource, 2017). Therefore, the simulation time of 20years is equivalent to **175200 hours**. The main idea here is to illustrate the maintenance activities for each component throughout the asset's lifetime. However, the equipment considered in the simulation includes three pieces of equipment from the Drive train module (generator, shaft, mechanical brake) and one piece of equipment from the rotor module (Blade).

Simulation consideration

- Model time – 175200 hours (20years)
- Modeling method – System dynamics
- Function used – “*pulseTrain(double startTime, double pulseWidth, double timeBetweenPulses, double endTime)*” (Anylogic, 2021)

The inputs for the flows are given in table 24. The input is derived from the different maintenance tasks for each equipment failure mode, as given in table 23. For example, one of the generator failure modes is STD (Structure deficiency), and the maintenance task assigned to it is given as P6. According to table 22, the interval for P6 is 1year, equivalent to 8760 hours, and the number of hours for the task is 6. Therefore the input of the flow representing this task is given as pulseTrain(8760, 6, 8766, 175200);

Where 8760 = Hours in 1 year
6 = Number of hours for the task
8766 = Hours in 1 year + number of hours for the task
175200 = Hours in 20 years

Table 24. Equipment Flow input description

System	Flow	Value	Description
Drive Train	Generator_STD_I1	`pulseTrain(8760,6,8766,175200)`	Maintenance activities for the Generator
	Generator_STD_P6	`pulseTrain(8760,6,8768,175200)`	
	Generator_STD_P3	`pulseTrain(17520,12,17532,175200)`	
	Generator_BRD_I1	`pulseTrain(8760,6,8766,175200)`	
	Generator_OHE_P4	`pulseTrain(4380,8,4388,175200`	
	M_Brake_STD_I1	`pulseTrain(8760,6,8768,175200)`	Maintenance activities for the Braking system
	M_Brake_STD_P5	`pulseTrain(8760,6,8768,175200)`	
	M_Brake_FTF_P5	`pulseTrain(8760,6,8768,175200)`	
	M_Shaft_VIB_I1	`pulseTrain(8760,5,8765,175200)`	Maintenance activities for the Shaft
	M_Shaft_VIB_P6	`pulseTrain(8760,5,8765,175200)`	
	M_Shaft_STD_P6	`pulseTrain(8760,5,8765,175200)`	
Rotor Module	Blade_VIB_I2	`pulseTrain(8760,4,8766,175200)`	Maintenance activities for the Blade
	Blade_VIB_P2	`pulseTrain(21900,12,21912,175200)`	
	Blade_STD_I2	`pulseTrain(8760,4,8766,175200)`	
	Blade_STD_P6	`pulseTrain(8760,9,8769,175200)`	
	Blade_STD_P2	`pulseTrain(21900,12,21912,175200)`	

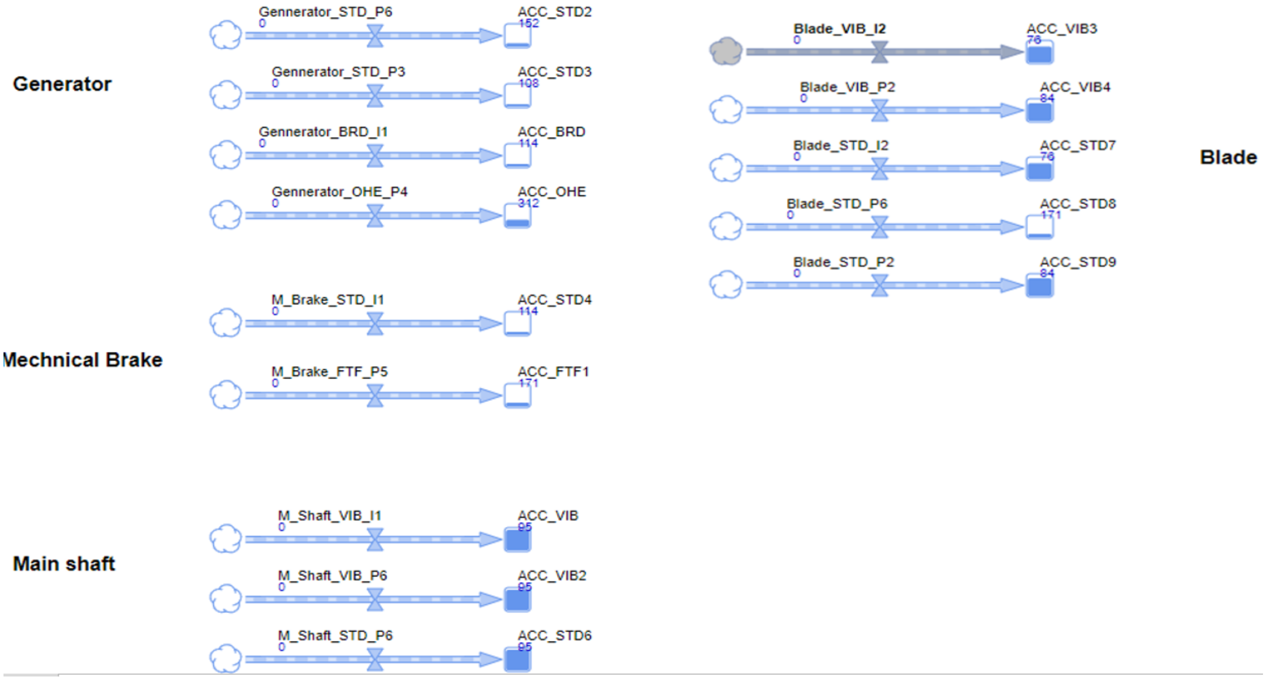


Figure 34. Equipment Flow diagram during simulation

Figure 34 represents the flow during simulation in Anylogic. Notice that each flow is attached to its separate box-like shape called “Stock” at each end. The Stocks are labeled according to the failure mode it represents, e.g., ACC_STD, where “ACC” stands for Accommodated. Each Stock carries a number of the accumulated maintenance time in hours for the specific maintenance task throughout the asset's lifetime. For instance, the Generator maintenance task “P4” for OHE (overheating) has the highest accumulated maintenance time of 312hours in 20years. It also confirms the argument that the generator is one of the highest causes of downtimes for the Direct-Drive wind turbine due to higher maintenance time. For the mechanical brake, task number P5 scores the highest maintenance time of 171hours in 20years. Other results can be seen in Figure 34.

Figures 35, 36, 37, and 40 simply illustrate the simulation graph of the maintenance activities and the accumulated maintenance time for the selected WT component and the different failure modes. Each line stroke in the left graph shows the maintenance interval, indicating that a maintenance operation is ongoing, and the wind turbine is shut down at that particular time. Thus, it illustrates that maintenance activities affect the availability of the wind turbine system, hence, decreasing the revenue generated.

Most maintenance campaigns occur once a year, though some maintenance actions are carried out based on the alert from the CMS or good knowledge about the failure rate. However, it is important to understand that these maintenance actions might not be carried out at the stipulated time due to some factors such as the weather condition, availability of repair materials, technicians, and the availability of vessels. These factors have been discussed in section 3.4.1 of this report. Moreover, some activities can take longer than the time used in this simulation if these factors come to play. The location of the wind farm is another factor that should be considered. Some wind farms are located further away from shore; therefore, travel time should be considered when estimating the overall maintenance time.

Generator

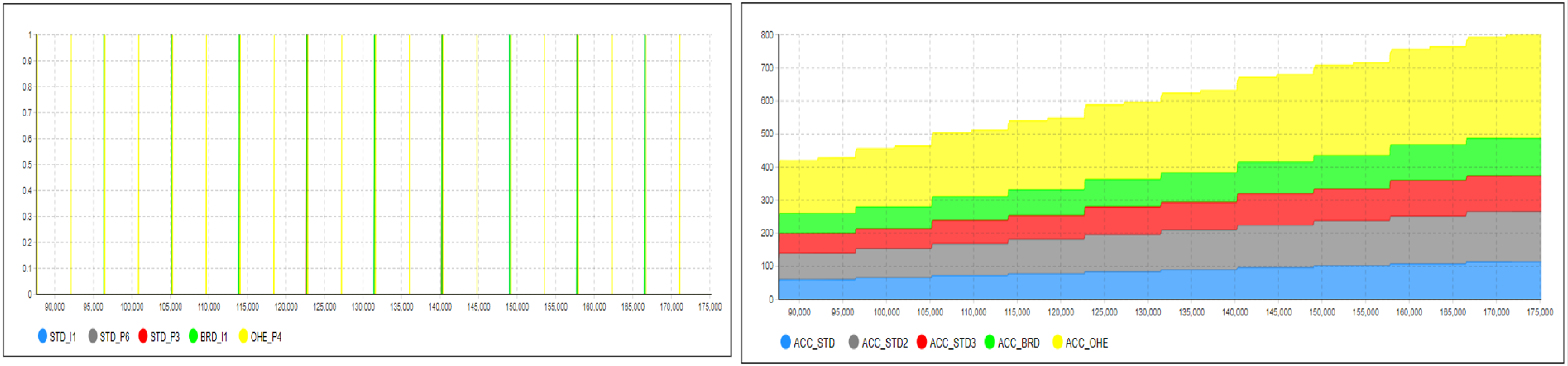


Figure 35. Simulated Maintenance timeline for generator (left) and the Accumulated maintenance time (right)

Mechanical Brake

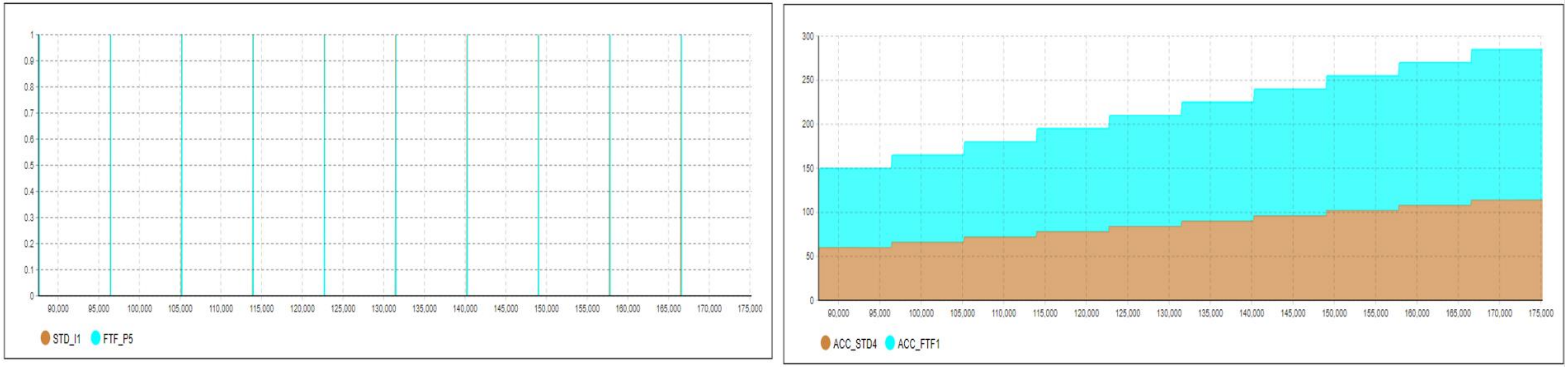


Figure 36. Simulated Maintenance timeline for main-shaft (left) and the Accumulated maintenance time (right)

Main shaft

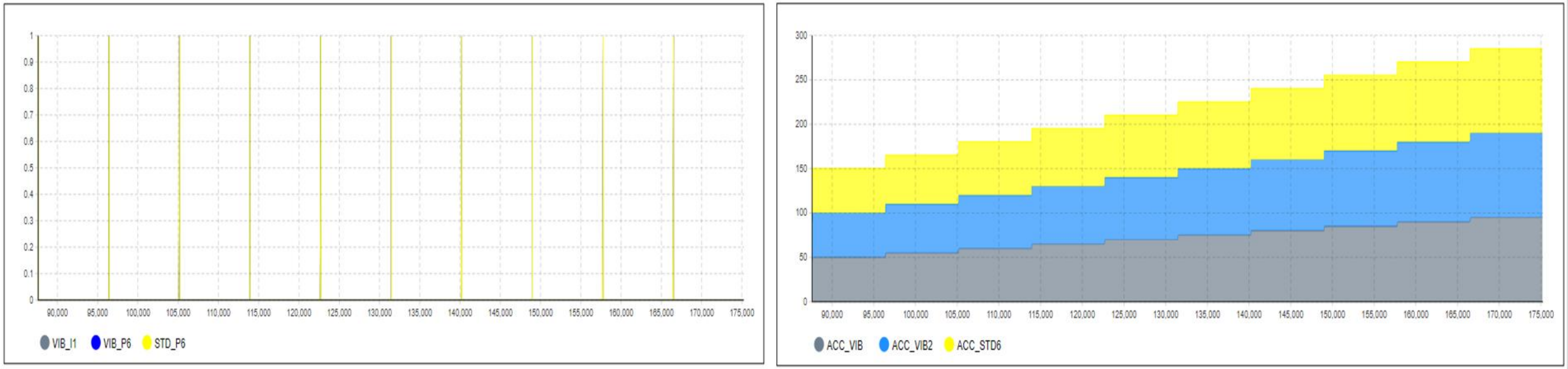


Figure 37. Simulated Maintenance timeline mechanical brake (left), and the Accumulated maintenance time (right)

Blade

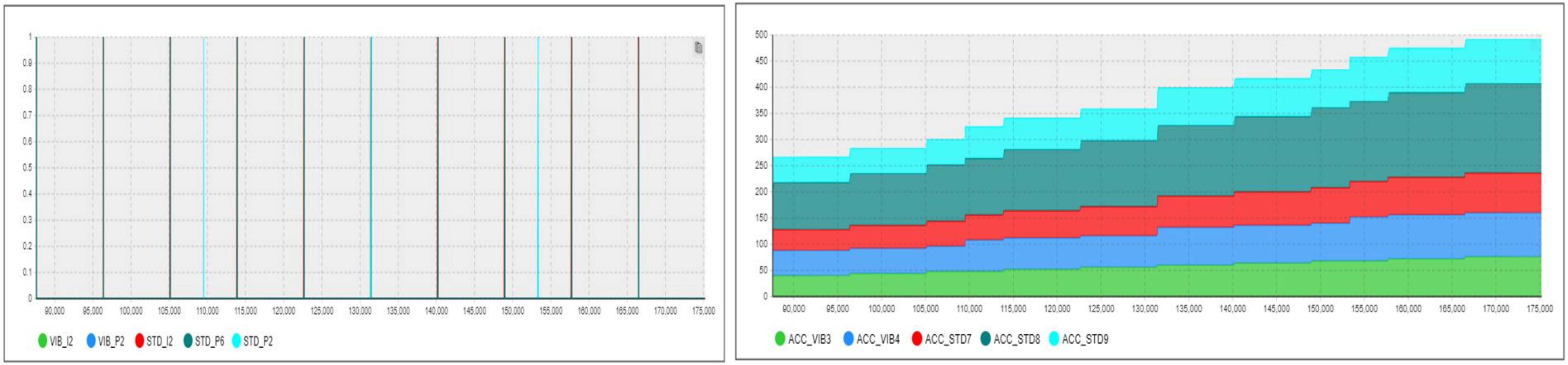


Figure 38. Simulated Maintenance timeline for the blade (left), and the Accumulated maintenance time (right)

5.6. Smart maintenance study

In the previous section, the maintenance task and interval were defined for the selected critical failure mode of the wind turbine based on the information collected through interviews with stakeholders and online sources. This section will try to develop a smart maintenance decision workflow to improve the maintenance operation.

The Smart maintenance concept aims to develop an integration of technology, machines, and humans to build an intelligent and improved maintenance system. By effectively using the Condition Monitoring system (i.e., aided by Big data analysis, machine learning) and the combination of modern autonomous technology, decision alternatives can be optimized to adequately managed maintenance activities. By so doing, reduce unnecessary maintenance action, maximize production, and reduce production cost & maintenance time.

5.6.1. Design process for Smart maintenance

This section presents the decision workflow for implementing Smart maintenance concepts for the critical failure mode of the wind turbine. However, the workflow is based on higher-level decisions making applied in the design phase of a project. Further decision processes can be drawn from each block when considering a lower level of decision-making.

As described in table 25, the case company Aker Solutions (AKSO) suggested some Smart maintenance use cases which apply to offshore wind turbines and are listed in. However, these use cases were adopted and grouped into three scenarios to fit into the proposed smart maintenance workflow

Table 25. Smart maintenance use cases

Smart Maintenance Use cases	Adopted Scenario	Comment
Critical Data Alerts	Condition monitoring scenario	This scenario is more related to data analysis based on the feedback from the condition monitoring system. The aim to rely on data-driven methods to optimize maintenance operation and carrying out maintenance at the optimal time. This has been explained in details in section 3.5.1
Estimating Remaining Useful life		
Digital maintenance planner		
Integrated inspection of Failure Data		
Drones, ROVs, AUVs, Robots Inspection	Autonomous Solution scenario	The scenario illustrates how modern technologies can be adopted for some maintenance activities. The aim is to reduce maintenance time and replace risky operations such as Inspection by rope access. Although AR and VR are more of connectivity technology, they can be placed in this category in order to simplify the workflow. This has been explained in details in section 3.5.2
Augmented reality (AR), Virtual reality (Deveci et al.)		

Not listed	Design out Scenario	This scenario involves eliminating the cause of failure. If the failure is eliminated, then resources will be channeled to other investment, thereby cutting down O&M cost
Digital twin	Loading profile	This involves operating the turbine in a manner that delays the deterioration rate of equipment by adjusting the load, such as reducing the speed or shutting down the turbine when there is low output

Some terms used in developing the workflow is to describe the flow is briefly defined in Table 26

Table 26. Description of some Terms used in the decision workflow

Terms	Description
Technical specification	Type, Capacity, input parameters, and operation of an equipment
Loading profile	Adjusting the load to delay equipment deterioration
Autonomous solution	Modern technologies that can operate without human intervention
Plug and Play	Quick repair or replacement
Design out	Involves Modification process to eliminate the cause of the failure or to improve the system
Prediction horizon	How far ahead can we predict the failure (weeks, months)
Opportunistic maintenance	Maintenance operation that is carried out at a time most suitable for the company

Figure 39 illustrates the Smart maintenance decision workflow. It is categorized into

- Risk-based Maintenance stage: This consists of the process previously done from sections 5.1 to 5.5 of this research work.
- Smart maintenance stage: The stage is further categorized into three use case scenarios which include Design out, condition monitoring scenario, and Autonomous solution scenario

It is essential to note that the workflow presented in Figure 39 is just the preliminary workflow developed in this study's early stage, which required further review. The correct and complete workflow is given and explains in detail after further research and verification & validation process with the research supervisors.

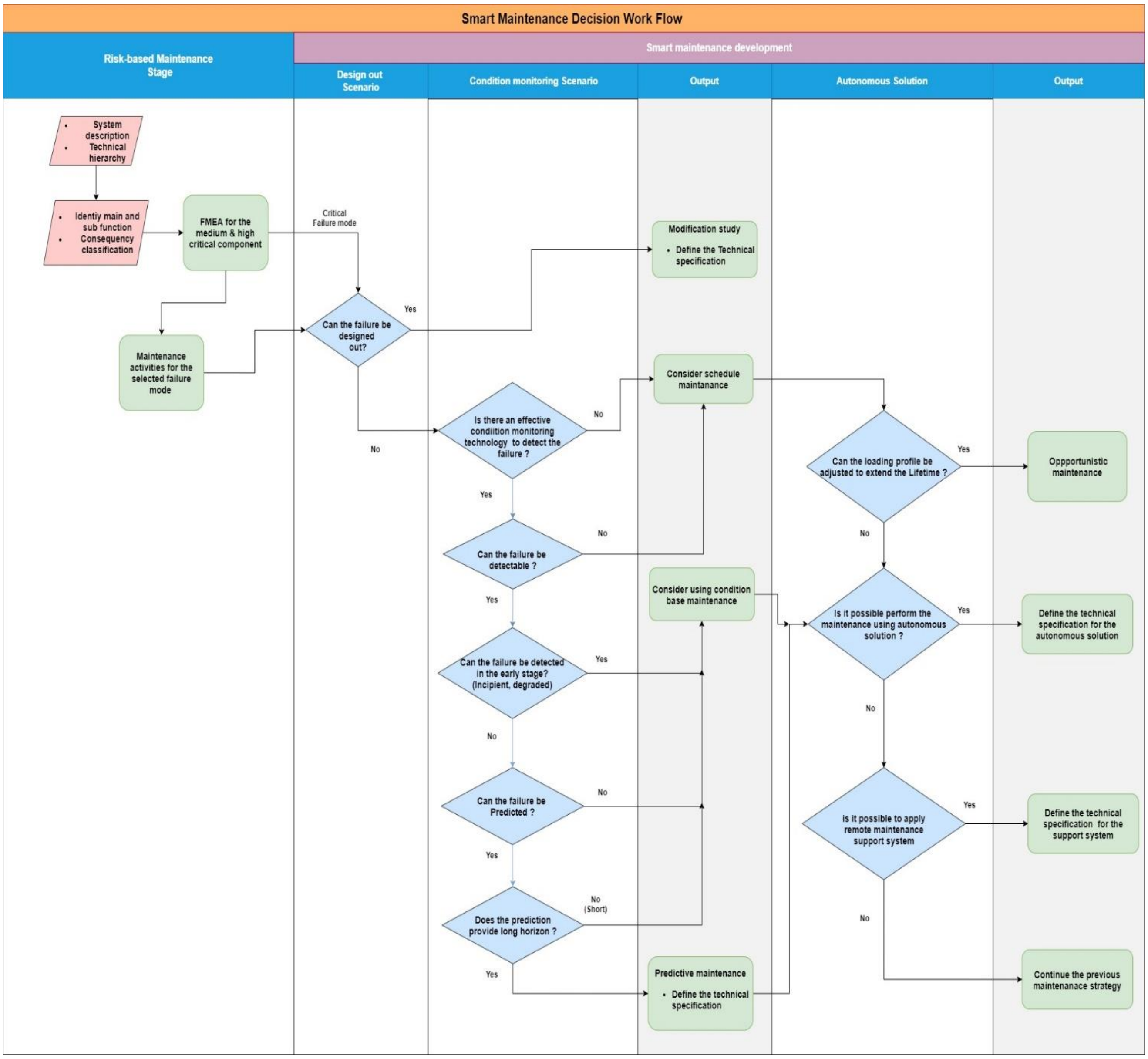


Figure 39. Smart maintenance decision workflow

5.6.2. Verification and Validation process (Smart maintenance decision workflow)

It is essential to perform verification and validation for the developed workflow to increase the trust and accuracy level of the workflow. The purpose of Validation is to check if the workflow meets the proposed requirement. The verification process is intended to assess the structure and interface of the workflow and check for errors that can affect the output of the workflow.

The verification and validation process was done by conducting a meeting with both my internal and external supervisors in Aker Solutions (AKSO) with many years of experience in the field of maintenance operations. All aspects regarding each workflow segment were discussed, and the comments are summarized in Table 27. I had a weekly meeting with my internal supervisor during the workflow development, so the workflow's input was adequately discussed and verified.

Table 27. Table of Verification and Validation

Aspect (Workflow segments)	Verification test (by Author)	Validation test (by supervisor)	Comments by supervisor	Comments by Author
Risk-based Maintenance stage	Ok	Ok with changes. See comment	Consider changing the shape of the block used in this segment to make it uniform	This stage was added in the workflow to explains the previous analysis carried out in order to create a connection to the proposed smart maintenance concept
Smart maintenance Stage	Ok	Ok	Clarify how you adopted the use case scenarios used in the flow chart	No comment
Design out scenario	Ok		Clarify the terminology used in the output	No comment
Condition monitoring scenario	Ok	Ok with changes. See comments	1. Consider introducing a new decision block at the beginning step of this scenario to justify the reason why to invest in condition monitoring technology 2. Clarify the necessary improvements to be considered before considering scheduled maintenance as an output 3. The decision block "can the failure be predicted" is not quite clear. Consider introducing a new decision block to clarify the reason why we want to predict the failure	The scenario was developed following the use case
Autonomous solution scenario	Ok	Ok, with changes. See comments	1. define the input going into the decision block 2. Change the terminology "Remote maintenance support" to avoid confusion with 3. Add a new decision block for "plug and play."	Explain more

5.6.3. Smart maintenance decision workflow Modification

Figure 40 presents the Modified workflow developed after the verification and validation process and further studies. The changes were made to the workflow considering the comments from the supervisors. A detailed description of this workflow is given below

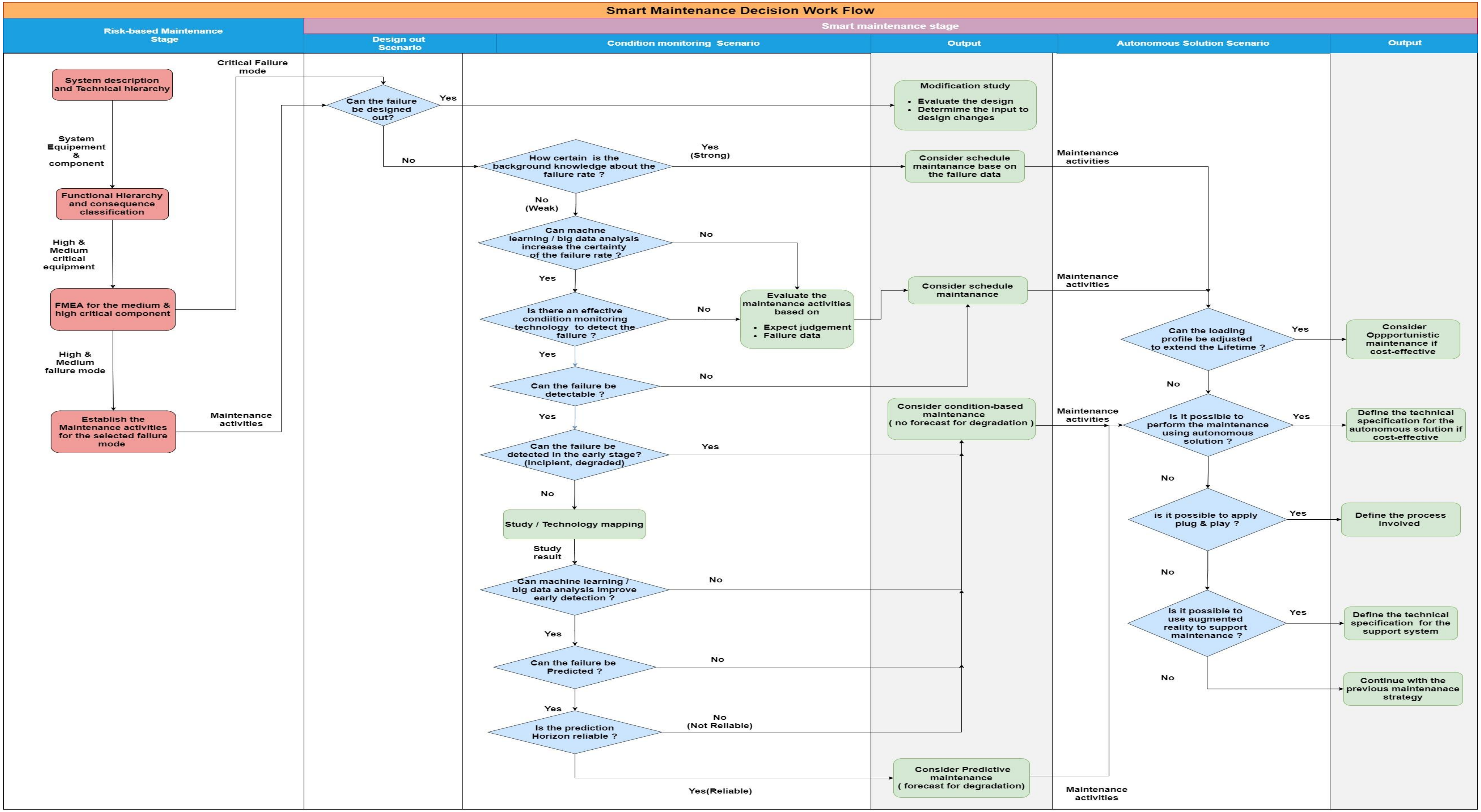


Figure 40. Modified smart maintenance decision workflow

5.6.3.1. Workflow Description

Risk-base maintenance stage:

As illustrated in Figure 40, this stage consists of the steps of the risk-based maintenance approach which has been presented in the previous sections. It comprises of technical hierarchy, where equipment and components are grouped according to their location in the system. Also, the Functional hierarchy and consequence classification were developed to define each system's main functions and subfunctions and classified them based on their criticality level. This can be said to be the first screen-out process to further analyze the high and medium critical functions. The FMEA was used to identify the root cause of failure and its effects on the system. Finally, different maintenance activities and intervals were assigned for the critical failure mode of each selected equipment of the turbine. All these processes are the necessary steps to clearly focus on the critical equipment of the wind turbine system. Input from this stage is needed to establish the Smart maintenance concept.

Smart Maintenance Development stage:

The manning study comprising of maintenance activities was created based on the most critical failure mode of the wind turbine (WT) components. This stage is categorized into three use case scenarios to establish a better maintenance concept for the offshore wind turbine system

- **Design out scenario**

As illustrated in the decision workflow, the design-out process involves deciding if the critical failure mode of a system in the WT can be designed out or not. If Yes, then a modification study should be carried out, and inputs required for the design change should be specified appropriately. This will help in determining the cost of such design change. The modification analysis will focus on eliminating the root cause of the failure to increase the reliability of the equipment. For instance, one of the critical failure modes of the WT generator is OHE (overheating); therefore, in the design out stage, the process tries to apply some changes to eliminate the failure causes, such as insufficient cooling and electric overload. These changes might be to install a different cooling system for the generator; therefore, the technical specification for such modification should be specified. In contrast, if the failure can not be designed out, the flow goes to the predictive scenario

- **Condition monitoring scenario**

It is important to note that condition monitoring (CM) technology is quite expensive. Therefore, before investing in CM technology, it is essential to check the certainty of the background knowledge about the failure, e.g., historical failure database, expect judgment. If the knowledge is strong, it is better to consider scheduled maintenance based on the failure data to save costs. Whereas, if the knowledge is weak, it is necessary to check if machine learning and big data analysis can increase the certainty of the failure data. If Yes, there is a need to check if there is an effective condition monitoring technology to detect the failure. If No is the case, evaluate the previous maintenance activities for that failure, considering expert opinion to determine possible improvements before considering schedule maintenance. However, not all failures have a condition monitoring system to detect them.

On the other hand, if there is a condition monitoring technology available, we need to assess the effectiveness of the technology and how early the failure can be detected. According to ISO 14224 standard, we have three stages of failure, incipient, degraded, and critical stage (section 3.6 explains these three failure stages). If the failure can be detected in the incipient or degraded stage, it implies that the CMS offers a good diagnosis; therefore, maintenance actions should be based on the notification from the condition monitoring system.

However, suppose the failure cannot be detected early, it implies that the CMS only gives a critical failure alert. In that case, it might be possible to carry out studies or technology mapping to identify any innovation or emerging technology that could improve the condition monitoring system (Big data, machine learning). Based on the result from this study, we can then decide if machine learning or big data analysis can aid improve the system's early failure detection. If No, then it better to do condition base maintenance. Whereas, if Yes, we proceed to check if the failure can be predicted.

In a situation where the failure cannot be predicted, condition base maintenance should be considered. In contrast, suppose the failure can be predicted; it is vital to check the reliability of the prediction horizon. If the prediction horizon is not reliable, it might be much better to carry out condition-based maintenance (without forecast for degradation), but predictive maintenance (with forecast for degradation) should be considered if the prediction horizon is reliable.

- **Autonomous Solution Scenario**

The predictive scenario's output suggested three maintenance strategies (scheduled maintenance, condition-based maintenance, and predictive maintenance) which were considered based on the decision flow. These maintenance strategies involve different activities depending on the equipment and task description. For example, a wind turbine blade inspection operation is typically done by rope access and requires 3 to 4 technicians; operation time can be about 6 to 12 hours. However, the Autonomous solution scenario tries to determine where and what maintenance activities can be automated. Therefore, this scenario comprises four decision blocks and output.

Suppose we are considering schedule maintenance for our equipment; the process flow checks to see if the loading profile for the turbine can be adjusted to delay the deterioration rate till the next maintenance interval. If this is possible, opportunistic maintenance should be considered if it is cost-effective. On the other hand, if we consider condition-based or predictive maintenance, check to see if it is possible to perform the maintenance activities using the autonomous solution. ROV, repair robots, and drones can replace some maintenance activities like blade and foundation inspection. As a result, several wind turbines in the farm can be inspected in the least possible time. Also, the risk associated with using rope access and human divers will be eliminated. If Yes, then there is a need to define the technical specification for the autonomous technology, such as the type, location, stability, camera quality, and the input machine learning algorithm to capture faults, e.g., crack, erosion, and corrosion.

If No, the process goes further to check the possibility of applying "Plug & Play." If Yes, the process involved should be defined. For example, some wind farms have a spare gearbox, therefore instead of carrying out the repairs on-site, the failed gearbox can be taken out, and the new gearbox is installed. In this way, the faulty gearbox is taken back to the onshore station for repair operations. This technique saves time and reduces downtimes. If Plug & Play is not applicable, the process further checks the possibility of using remote maintenance systems such as augmented reality to support maintenance activities. If it is possible to use a remote maintenance support system, the technical specification needs to be defined. If No, continue with the initial maintenance activities already defined in the manning study.

Conclusively, the Design out scenario tends to eliminate the failure, which means there will no need to carry out maintenance for that particular failure mode. The predictive scenario focuses on selecting a better maintenance strategy, while the Autonomous scenario tends to apply modern technology for some maintenance activities.

5.6.4. Implementation of the smart maintenance workflow

In order to implement smart maintenance, this process follows the decision workflow illustrated in Figure 40 above. The analysis was done in excel to present a better visual of the data. However, more information is needed from the condition monitoring system providers to complete the implementation process.

In this process, as shown in Table 28 below:

- X – denotes No Information
- N/A – denotes Non-Applicable

Table 28 presents the Baseline maintenance concept (left) and the Smart maintenance concept (right). The design out and preventive scenario focuses on the failure mode to determine if the failure can be designed and if the failure is detectable and predictable. On the other hand, the autonomous scenario focuses on the maintenance activities (I, I2, P1, P2, P3, P4, etc.) to determine if an automated system such as drones, robots, and AUV can use for some maintenance activities. It also indicates the activities where AR and VR can be applied as a means of support during the maintenance operation

Table 28. smart maintenance concept worksheet

Baseline Maintenanace Concept (Preventive maintenance) Offshore Wind Turbine system (Direct Drive)								Smart/Intelligent maintenance concept										
								Design out scenario	Predictive scenario						Loading profile	Autonomous solution scenario		
Wind Turbine system/section	**Equipment unit**	**Function failure**	**Potential Failure Mode**	**Task No.**	**No. of Person**	**Estimated PM Hours**	**Discipline**	**Design out**	**Failure knowledge**	**Detectable**	**Dectection Stage**	**Prediction Ability**	**Predictive Horizon**	**Operating profile**	**Autonomous solution**	**Plug and Play**	**Maintenance support system**
Which system in the wind turbine is to be Investigated	What are the Equipment in your sytem	What is the actual functions that failed	In what way can the function fail	What is the number assigned to the task	How many Technicians are needed for the job	What Is the duration of the Maintenance task take	What is the department responsible for the task	Can the design be modified to eliminate the cause of failure	is there strong knowledge about the failure	Can the failure be detected through condition monitoring	Insipient, Degraded, Critical	can the failure be predicted by applying machine learning and big data analysis	How reliable is the predict horizon (Long / Short)	is it possible to adjust the operating profile to extend yes/ NO	is it possible to use drones, AUV Robotics for the maintenance task	Can we reduce the time for replacement through plug &play	is it possible to apply AR, VR
Rotor Module																		
	Pitch ystem	**Fail to regulate / fail to position the blade towards the of wind direction for energy capture**	**FTR**	**M1**	**N/A**	**N/A**	**Electrical**	**X**	**X**	**Yes**	**X**	**X**	**X**	**X**	**N/A**	**N/A**	**N/A**
				P1	**3**	**5**	**Electrical**								**N/A**	**N/A**	**N/A**
				T1	**2**	**N/A**	**Electrical**									**N/A**	**N/A**
				P3	**3**	**12**	**Mechanical**								**X**	**Partially**	**Yes using AR technology (Smart glasses)**
			STD	**I1**	**3**	**6**	**Mechanical**	**X**	**X**	**Yes**	**X**	**X**	**X**	**X**	**NO**	**N/A**	**Yes using AR technology (Smart glasses)**
				M1	**N/A**	**N/A**	**Mechanical**								**N/A**	**N/A**	**N/A**
			OHE	**P1**	**3**	**5**	**Mechanical**	**X**	**X**	**Yes**	**X**	**X**	**X**	**X**	**N/A**	**N/A**	**N/A**
	Blade	**Fail to rotate / covert energy from the wind to enable power production**	**VIB**	**M2**	**N/A**	**N/A**	**N/A**	**X**	**X**	**Yes**	**Degraded**	**X**	**X**	**X**	**N/A**	**N/A**	**N/A**
				P2	**4**	**12**	**Mechnical**								**Yes using crawler robot**	**N/A**	**X**
				I2	**3**	**4**	**Mechnical**								**Yes by using drones**	**N/A**	**X**
				P6	**3**	**9**	**Mechnical**								**No**	**N/A**	**N/A**
			STD	**I2**	**3**	**4**	**Mechnical**	**X**	**X**	**Yes**	**X**	**X**	**X**	**X**	**Yes by using drones**		**X**
				P2	**4**	**12**	**Mechnical**								**Yes using crawler robot**	**N/A**	**X**
Drive-Train Module																	
	Main shaft	**inadequate / fail to tranfer the rotational mechanical energy to the generator**	**STD**	**I1**	**3**	**6**	**Mechanical**	**X**	**X**	**Yes**	**X**	**X**	**X**	**X**	**NO**	**N/A**	**Yes using AR technology (Smart glasses)**
				P6	**3**	**8**	**Mechanical**									**N/A**	**N/A**
			VIB	**M2**	**N/A**	**N/A**	**N/A**	**X**	**X**	**Yes**	**Degraded**	**X**	**X**	**X**	**N/A**	**N/A**	**N/A**
				P6	**3**	**5**	**Mechanical**									**N/A**	**N/A**
	Mechnical Brake	**Fail to reduce the rotational speed or fail to stop the turbine system during emergency**	**STD**	**I1**	**3**	**6**	**Mechanical**	**X**	**X**	**Yes**	**X**	**X**	**X**	**X**	**Partially using drones**	**N/A**	**Yes using AR technology (Smart glasses)**
				M1	**N/A**	**N/A**	**N/A**								**N/A**	**N/A**	**N/A**
			FTF	**P5**	**3**	**12**	**Mechanical**	**X**	**X**	**Yes**	**X**	**X**	**X**	**X**		**N/A**	**Yes using AR technology (Smart glasses)**
				M1	**N/A**	**N/A**	**N/A**								**N/A**	**N/A**	**N/A**
	Generator	**Fail to convert the rotational mechanical energy to electrical energy**	**STD**	**I1**	**3**	**6**	**Mechanical**	**X**	**X**	**Yes**	**X**	**X**	**X**	**X**	**Partially using drones**	**N/A**	**Yes using AR technology (Smart glasses)**
				P6	**3**	**6**	**Mechanical**									**N/A**	**N/A**
				M2	**N/A**	**N/A**	**N/A**								**N/A**	**N/A**	**N/A**
				P3	**3**	**12**	**Mechanical**									**Partially**	**Yes using AR technology (Smart glasses)**
			BRD	**M1**	**N/A**	**N/A**	**N/A**	**X**	**X**	**Yes**	**X**	**X**	**X**	**X**	**N/A**	**N/A**	**N/A**
				I1	**3**	**6**	**Mechanical**								**Partially using drones**	**N/A**	**Yes using AR technology (Smart glasses)**
			OHE	**P4**	**3**	**8**	**Mechanical**	**X**	**X**	**Yes**	**Degreded**	**X**	**X**	**X**		**N/A**	**Yes using AR technology (Smart glasses)**
				M1	**N/A**	**N/A**	**N/A**								**N/A**	**N/A**	**N/A**

5.6.4.1. Smart Maintenance Timeline

In section 5.6.3, the Smart maintenance decision workflow has been established. Therefore, the workflow will be applied to create a new maintenance timeline that shows the benefit of using the Smart maintenance concept. The information present in Table 28 is not enough to implement the three scenarios as presented in the workflow. Nevertheless, only the autonomous solution scenario will be applied to the Blade maintenance activities to simulate the new timeline

The following decision was made based on the decision workflow

- Is it possible to perform Blade maintenance using an autonomous solution? YES
- If Yes, define the specification for the technology if cost-effective

Bernardini et al. (2020) presented the possibility of utilizing an intelligent & collaborative IMR (inspection, maintenance, and repair) for the physical component of the offshore wind turbine, such as the blade, nacelle, and tower. Utilizing the autonomous solution in some maintenance activities can reduce the repair time, the safety risk involved, and the number of technicians required, hence lowering the cost (Bernardini et al., 2020).

Two technology that can be used for blade maintenance includes;

1. Autonomous drone and
2. Repair robot with cross arm

Figure 41 describes the process of this scenario. The crew transfer vessel (CTV) conveys both the technician and the drone and robot to the wind farm for blade inspection, maintenance, and repair. The technician set up the drone and deployed it for inspection operation on the wind turbine blade. The drone can autonomously navigate around the wind turbine blade and feed the inspection result to the maintenance technician. The crawler robot is deployed to carry out the blade maintenance and repair based on the inspection result. It can autonomously navigate with the help of sensitive tactile sensors to each blade section that requires intervention. In addition, the crawler robot has a flexible articulated cross arm that enables it to performs blade surface treatment, remediate cracks & delamination. The updated information about the implementation of this autonomous solution scenario is given in Table 29.

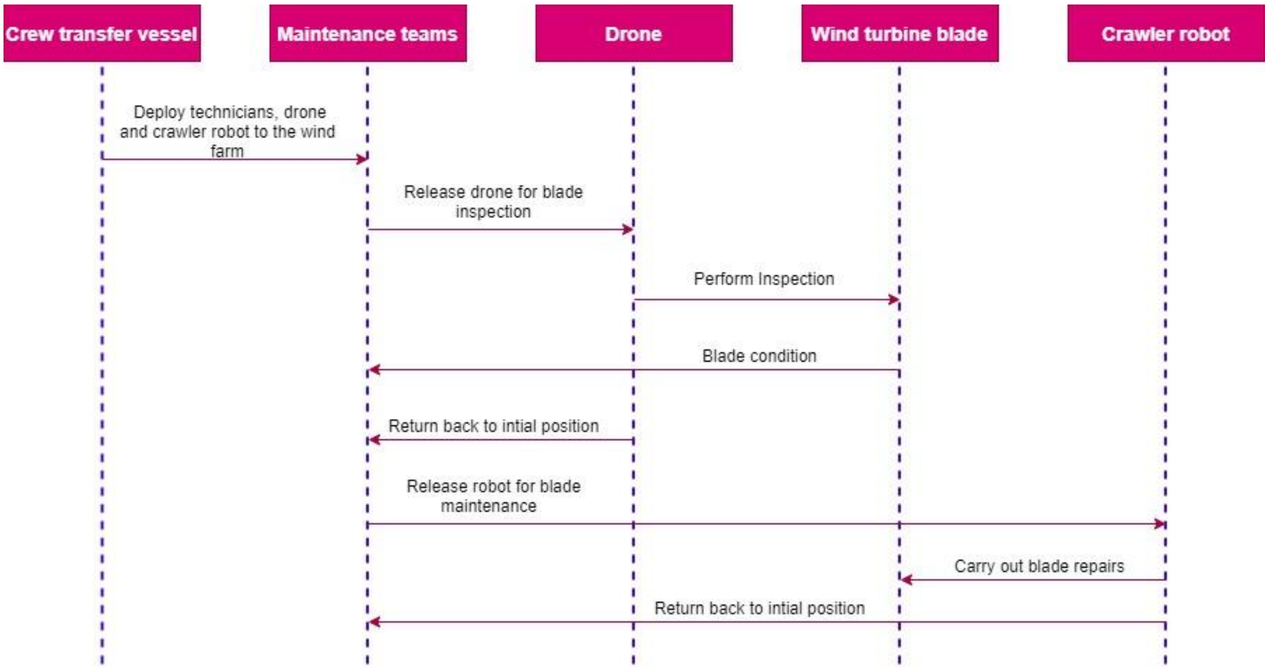


Figure 41. Sequential diagram of the autonomous solution implementation process

Table 29. Implementing Autonomous solution scenario for Blade Maintenance

Implementing Autonomous solution scenario for Blade Maintenace							
Wind Turbine system/section	**Equipment unit**	**Function failure**	**Potential Failure Mode**	**Task No.**	**No. of Person**	**Estimated PM Hours**	**Automous solution**
Which system in the wind turbine is to be Investigated	What are the Equipment in your sytem	What is the actual functions that failed	In what way can the function fail	What is the number assigned to the task	How many Technicians are needed for the job	What Is the duration of the Maintenance task take	What is the technology used
Rotor Module							
	Blade	**Fail to rotate / covert energy from the wind to enable power production**	**VIB**	**P2**	**2**	**6**	**Carry out task using autonomous crawler robot**
				I2	**1**	**1**	**Carry out task using autonomous drone**
				P6	**2**	**4**	**Carry out task using autonomous crawler robot**
			STD	**I2**	**1**	**1**	**Carry out task using autonomous drone**
				P2	**2**	**6**	**Carry out task using autonomous crawler robot**

In table 29, notice that the technology used for each maintenance task has been specified based on the autonomous technologies. Information regarding the number of technicians required and the number of hours when using an autonomous drone was derived based on expert opinion (Odin, 2021). Changes were made to the input of the flow, as shown in Table 30, to simulate the new timeline

Table 30. Blade Flow input description

Rotor Module	Blade_VIB_I2	`pulseTrain(8760,1,8766,175200)`	Maintenance activities for the Blade using autonomous drone and crawler robot
	Blade_VIB_P2	`pulseTrain(21900,6,21912,175200)`	
	Blade_STD_I2	`pulseTrain(8760,1,8766,175200)`	
	Blade_STD_P6	`pulseTrain(8760,4,8769,175200)`	
	Blade_STD_P2	`pulseTrain(21900,6,21912,175200)`	

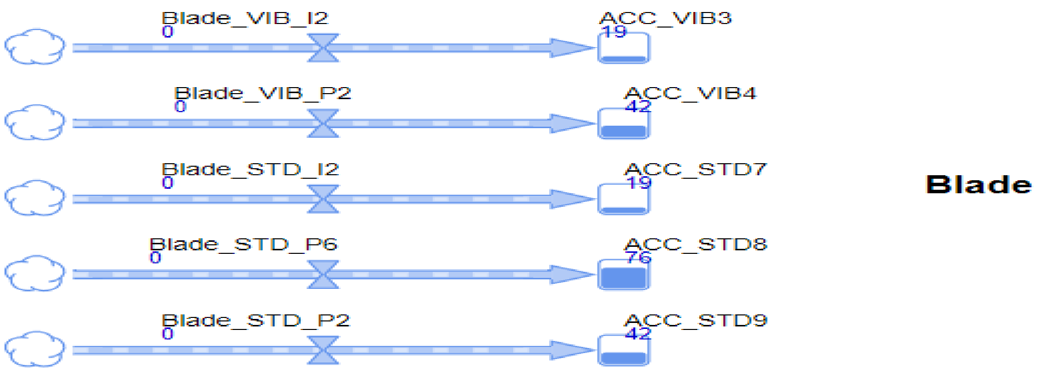


Figure 42. Blade Flow diagram during simulation

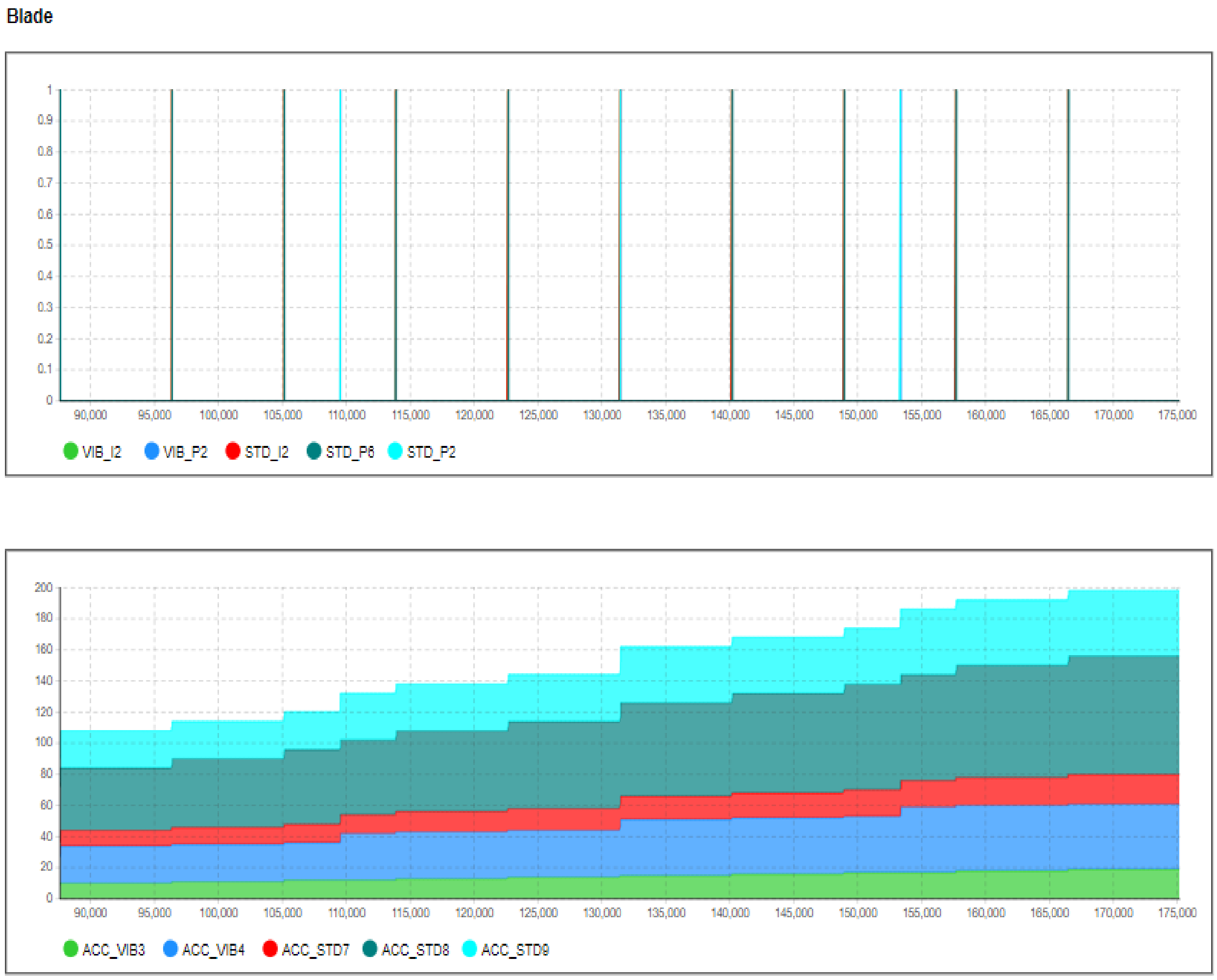


Figure 43. Simulated Smart Maintenance timeline for the blade (up) and the Accumulated maintenance time (down)

Figure 42 above represents the flow simulation of the blade using the autonomous solution, and the accumulated time for each maintenance task is shown in the Stock. In Figure 43, each flow has generated both the graph of the timeline (with the line stroke) showing the maintenance interval and the accumulated operation time graph throughout the wind turbine blade lifetime. Here, task number P6 scores the highest maintenance time of 76 hours in 20years, which can be seen to have the largest shaded area in the graph (representing ACC_STD8). Both ACC_VIB3 and ACC_STD7 scored a total of 19 hours.

5.7. Comparison Study

This section is the last stage of the analysis workflow. The purpose is to compare the result from the baseline simulated maintenance timeline and the Smart maintenance timeline to identify the added value and the challenges. The information obtained for this study was only enough to implementing the autonomous solution for blade maintenance. Therefore section will compare the results from the graphs of both blade maintenance timelines in Figures 40 and 45.

The table provides the comparison between the Blade baseline maintenance concept and the Smart maintenance concept. The comparison factors are based on the attributes of Figures 38 and 43.

Both concepts have applied different maintenance techniques maintenance which is indicated in Table 31. There is no difference between the maintenance timeline graph in Figures 38 and 43 because the maintenance interval was the same in both concepts. It will require the implementation of the condition monitoring scenarios in order to restrategize the maintenance interval. Nevertheless, significant changes can only be noticed in the accumulated maintenance time for different maintenance activities highlighted in Table 30. The total maintenance time (Manning hour) for the blade might experience a 60.1% decrease throughout the system's lifetime if the autonomous solution is utilized for maintenance. Blade maintenance is also one of the major causes of turbine downtimes. Moreover, a reduction in the maintenance time might increase the system's availability by 39.83%.

However, it is important to note that this result can vary depending on the factor considered, such as weather conditions, vessel availability e.t.c.

Table 31. Comparison between Blade

Blade Activities	**Baseline Concept**	**Smart Concept**	**Percentage Decrease**
Maintenance technique	Using Rope access	Using Drones, Repair robot	N/A
Maintenance Event	Same interval	Same interval	N/A
ACC-VIB3 (Hours)	76	19	75%
ACC_VIB4 (Hours)	84	42	50%
ACC_STD7 (Hours)	76	19	75%
ACC_STD8 (Hours)	177	76	57.06%
ACC_STD9 (Hours)	84	42	50%
Total Accumulated maintenance time in 20 years (Hours)	497	198	60.16%
Availability gained			39.83%

Chapter 6

6. Discussion and Recommendation

This research aims to create a maintenance concept for offshore wind turbines and develop a Smart maintenance concept (use case scenarios) to improve the maintenance operation for the critical component of the offshore wind turbine system. For this reason, several engineering steps were established. However, this section consists of relevant discussions and limitations of each step taken in the analysis chapter; a general recommendation and generalizability will also be discussed at the end of this chapter. Figure 31 presented in chapter 5 illustrated the steps adopted for the analysis; therefore, this discussion chapter will also be sub-divided and discussed according to those steps.

System description and Technical hierarchy:

These are the first two steps of the analysis chapter. The system description illustrated the significant parts of the direct drive wind turbine system and how they interact in the production process. It provided a clear picture of how the Direct-drive wind turbine operates compared to the typical gear-driven wind turbines (WT). However, the technical hierarchy was developed using the ISO 14224 standard, which showed how the WT is technically built. This analysis illustrated the main features in a hierarchy process and the proper grouping of items according to their location to enable adequate maintenance management. It indicated the equipment and the maintainable component in each wind turbine system, which has provided the layout for the next step of analysis (the functional hierarchy). The hierarchy level demonstrates a correlation with the previously developed wind turbine taxonomy presented by (Tavner, 2012), though with different level terminology. Also, the result proves that using the ISO 14224 standard provides a better guideline and level terminology in developing technical hierarchy for the wind turbine compared to others.

- **Limitations:**

Developing the wind turbine Technical hierarchy is a very complex process. It is hard to determine the hierarchy level to place some items due to a lack of a proper block diagram of the selected system and inadequate knowledge. For this reason, not all items in the direct drive wind turbine were identified. Although the adopted ISO 14224 standard provided better hierarchy terminology, the examples stated are related to oil & gas equipment, making it difficult to classify wind turbine equipment. The most used data for the development process is similar to the Relia wind taxonomy referenced by (Tavner, 2012) & (Kaidis, 2014). Moreover, they were based on a gear-driven WT and are of old design type and lower capacity. Therefore, the technical hierarchy developed in this research does not identify the improved features of the modern wind turbine system.

Functional Hierarchy and Consequence classification:

The function hierarchy and consequence classification were developed using the Norsok-Z-008 standard. According to the layout in the Technical hierarchy, the main function and sub-function of the equipment unit were defined. The results indicate that the WT system unit can have multiple Main-functions depending on the equipment placed under it. The Norsok-Z-008 standard provided a list of main-function, some of which were adopted in the process. However, following the theory in the standard, this study suggested new main functions to fit the wind turbine system based on engineering judgment, e.g., wind-catching, braking, housing, positioning (see the list of functions in table 13). The sub-function was also adopted from the Norsok-z-008 standard, which has provided the basis for classifying these functions according to their criticality level.

The consequence classification analysis indicated high criticality for functions of the equipment in the drive train and electrical modules such as the generator and power circuits. This result supports the argument presented by (Tavner et al., 2006), which suggested that the direct-drive WT is less reliable than the gear-driven WT due to an increased generator and electric system failure. Another reason is that the generator experiences a high level of stress due to the absence of the gearbox, thereby increasing the failure rate. In addition, the high cost of materials for direct-drive generators is another factor making it highly critical equipment in the WT. There is no available literature implementing the Norsok-Z-008 standard for the wind industry; therefore, this analysis provides new original insight into consequence classification for the wind turbine system.

- **Limitations:**

The risk decision criteria used for the consequence classification are related to the oil & gas sector. Safety and environmental factors are highly prioritized in the oil and gas sector because equipment failure can be very hazardous as well as have huge financial consequences. Cases such as oil spills and fire disasters can lead to serious accidents and damage to the environment. In contrast, it is mostly minor or negligible for the offshore wind industry since the failure function of the wind turbine components does not lead to fatality or pollution to the environment. Based on expert opinion, most injuries are minor such as cuts in the finger. However, the risk decision criteria used do not entirely fit with the offshore wind industry in terms of safety and environmental parameters. The data used for the cost and failure frequency ranking were derived from the reliability and maintainability dataset published by (Carroll et al., 2016). This data does not cover modern direct-drive wind turbine technology. Cost data are still treated as highly confidential in the wind industry. Moreover, not all repair cost for the different component function was given in the dataset. Some assumption was made for the repair cost and production classification based on the insight provided in the dataset.

Failure Mode and Root cause Analysis (FMEA):

The FMEA focused on the high and medium-level critical equipment resulted from the consequence classification. The result indicates that the critical failure mode of the generator has a high-risk priority number (RPN) followed by equipment in the electrical module, such as the converter and power system. These results are in relation to the FMEA result presented by (Kahrobaee & Asgarpoor, 2011), which showed that generator failure is more critical for the direct-drive WT. Contrary to the rating scale used in other FMEA research, the rating scale adopted in this research was presented by (Arabian-Hoseynabadi et al., 2010), and it makes the FMEA methodology more practical for wind turbine systems. The result also provides a clearer understanding of the main root cause of failure for each of the selected wind turbine equipment, making it easier to set up a suitable maintenance plan.

- **Limitations:**

One main challenge in this step was assigning the rating for the severity, frequency, and occurrence to the different failure modes and root causes. Failure rate and operational data are well protected and seen as top secret in the company. For this reason, there is no information about the failure rate of the modern wind turbine in the market. Most available data are for old WT design and a lower capacity which are not detailed enough. Therefore, there is some degree of uncertainty in this analysis. However, to cover all the parameters, some reasonable assumptions were made based on information provided in previous research and will require further verification. Although the FMEA provided a certain level of understanding about failure frequency related to the direct-drive WT, the generalizability of the result is limited since the failure rate differs depending on the location of the WT and design factor.

Maintenance task selection and Manning study:

This study provided a good insight into the maintenance activities of turbine equipment, mainly focused on the drive-train equipment and the failure mode with a high-risk priority number (RPN) in the FMEA. The information used was based on expert opinion through interviews. Although literature confirms that most maintenance campaigns occur once a year, some maintenance actions are carried out based on the CMS or good knowledge about the failure rate. The results from the simulation graph in Figures 35, 36, 37 & 38 of section 5.5.2 demonstrate how maintenance action affects the overall availability of the WT system. It also indicates that the generator and blade maintenance are the major causes of downtime in the direct-drive wind compared to the typical wind turbine where the gearbox has both the highest failure rate and cause of downtimes. This analysis contributes a clearer understanding of the typical maintenance operation of the WT, which should be taken into account when considering improvement strategies (smart maintenance concept)

- **Limitation:**

The biggest challenge here was getting maintenance data for the selected system. The offshore wind market is highly competitive, and operational data is confidential. The available maintenance information is mostly related to onshore WT. Although insight into maintenance operations was obtained through the interview conducted, this information is not detailed enough due to the confidentiality factor. For information regarding maintenance time and workload, this research mainly dependent on analysis from the report "*Failure rate, repair time and unscheduled O&M cost analysis of offshore wind turbines,"* which was published by (Carroll et al., 2016). Therefore, these factors limit the reliability and generalizability of the result from this maintenance study. It is also important to note is that maintenance activities offshore are high risk compared to onshore. In reality, the simulated maintenance timeline discussed in section 5.5.2 is not so practical due to factors that affect maintenance operation, such as weather conditions, availability of repair materials, technicians, and the availability of vessels. Based on expert opinion, WT technicians can take up to one year before attending to their client, especially for blade maintenance. This is because there are limited experienced maintenance personnel in the offshore wind industry, which also confirms that the offshore wind turbine O&M is still at the early stage compared to the offshore oil & gas sector. However, if these factors come to play, maintenance activities can take a much longer time compared to the time stated in the simulation. For these reasons, it is challenging to define the actual maintenance timeline.

Smart maintenance concept:

This study presents a decision workflow for implementing Smart maintenance concepts for the critical failure mode of the wind turbine. The workflow suggested three scenarios: the design out, condition monitoring, and autonomous scenario, as shown in Figure 40 of section 5.6.3. The workflow illustrates a clearer understanding of different decision steps that should be considered when selecting a better approach to optimize the maintenance operation for critical components of offshore wind turbine systems. In addition, this study demonstrated the benefits of smart maintenance by implementing the autonomous scenario for blade maintenance. The result shows a significant decrease of 60.1% in the total maintenance time across all maintenance activities using autonomous technology such as drones and crawler robots. It also implies that there would be a 38.8% increase in the availability of the wind turbine since maintenance is carried out in a shorter time. Furthermore, judging from the decision workflow, it would be more interesting and beneficial to rely on a data-driven method for maintenance optimization through implementing the condition monitoring scenario. However, more information is required to achieve this.

- **Limitation:**

The challenge was getting the required information from the condition monitoring system to implement the predictive scenario successfully. The case company (Aker solution) currently does not have this data, though the effort made to get these data from the condition monitoring provider was unsuccessful. Due to the lack of these data, only the autonomous solution scenario was implemented. Thus, it is not enough to confirm the overall effectiveness of the smart maintenance concept.

6.1. Recommendation and Further works

The previous section has highlighted the limitations of each step adopted in this research, and some recommendations can be drawn from it. It is evident that the offshore industry is currently moving further to deeper waters where the direct-drive wind turbine and floating foundation are considered more beneficial. Therefore it is important to update the technical hierarchy to identify the improved features of the modern wind turbine system. In order to get a reliable consequence classification for the WT component, it would be more beneficial to develop the correct risk decision criteria that will match the offshore wind situation. This thesis tries to identify the critical failure mode and rating of the function failure severity, occurrence, and detection for the wind turbine component, but the data used is not detailed enough. For this reason, the offshore wind industry needs a open-access database like OREDA(Offshore and Onshore Reliability Data). However, this will require all key stakeholders to come to an agreement to share useful information for such a database to exist. Operational data are top company secret, especially in the offshore wind industry where competition is high. The baseline maintenance concept created needs further contribution to cover all systems in the turbine and enable adequate maintenance planning, considering some factors affecting maintenance such as weather window vessel availability. Even though the developed smart maintenance workflow showed positive results by implementing one scenario, it is still uncertain if the result will be beneficial for other scenarios. Therefore, implement the three scenarios defined will be interesting to show the whole lifetime benefit of utilizing the model. This can be achieved by obtaining the missing information about the Condition monitoring system in order to update the model. In addition, it might be baffling to understand the overall meaning of the term Smart maintenance due to inconsistency in several definitions. Some other buzzwords such as intelligent or digitalized maintenance might mean the same depending on the context. A general and more clarified definition is needed to improve the understanding of the term.

Further research work originating from this thesis includes

1. Develop a risk decision criteria matrix for criticality classification of the offshore wind turbine system

2. Efforts should be made to get more data about the condition monitoring system to implement the complete smart maintenance concept considering multiple use case scenarios such as the predictive scenario.
3. Developing maintenance concept for offshore wind turbine considering external factors like the weather condition
4. Evaluating the cost of implementing smart technologies for maintenance activities

6.2. Generalizability

It is important to discuss the generalizability of the steps adopted in the research to see its relevance in terms of scale, wind farm location, and other influencing factors. In other to illustrates this, two questions have been briefly discussed. However, the answer is based on the author’s opinion about the work.

1. Are the steps adopted in this research relevant for a larger scale project*? Answer- Yes*

This research was limited to only the component inside the nacelle and the blade. However, the steps taken can also be applied when considering the full-scale wind farm. This means that we move from just the turbine to the whole wind farm, considering multiple wind turbines and the balance of plants such as the transformers, foundation, cable, and offshore transmission substation. Adopting the steps in the methodology will be effective because it follows the risk base maintenance approach, though further detailed studies are required, especially for the offshore transmission substation. In addition, efforts must be made to updating the risk criteria matrix used, the critical failure modes, and the necessary maintenance operation. The big challenge will be obtaining the information needed to carry out the full-scale analysis. Unfortunately, this information is not publicly available.

2. Can the developed Model be applied in a different context*? Answer- Partially*

This research has considered a generic case of a direct-drive turbine mostly suitable with Siemens Gamesa WT design and North-sea location. The model developed is quite applicable in a different context, i.e., from one wind farm to another wind farm where the context is different. Though, there will be some variations. If the context is changed, then the influencing factor will equally change. The model focuses more on the critical failure mode of the system. However, when considering a different design of a direct-drive turbine, the component type and failure pattern might not be the same. Note that external factors such as weather and wind farm location and wind conditions will also influence the wind turbine component failure rate and maintenance method. This justifies that the developed workflow can only be used as a guideline. Further studies are required when considering a specific case with influencing factors such as turbine design, farm site, company budget e.t.c.

7. Conclusion

This chapter presents a summary of this research. It comprises the main conclusion regarding the formulated research question and subsequent conclusions regarding the results from the analysis chapter. A general contribution of this research will also be presented at the end.

This thesis aims to answer the research question:

"How can Smart maintenance concept be applied to improve the maintenance of critical equipment in an offshore wind turbine"?

In order to apply Smart maintenance, firstly, follow the steps of the risk-based maintenance approach (based on Norsok-Z-008), taking into account the difference in risk assessment criteria and additional equipment that is not in oil & gas such as the wind turbine blade. There is also a need for reliable failure data (Failure mode, MTTF, MTBF) and expert opinion to define special functions. Secondly, the smart maintenance concept study can be integrated at the latter stage of the risk-based maintenance, where the smart maintenance decision workflow will be utilized. The decision workflow in Figure 44 presents the steps in the risk-based maintenance approach and the Smart maintenance concept consisting of three scenarios that illustrate the steps, decision processes, and actions involved in applying Smart maintenance concepts for critical equipment of offshore wind turbines. The workflow was verified and validated based on expert judgment, thereby increasing the potential for future adoption.

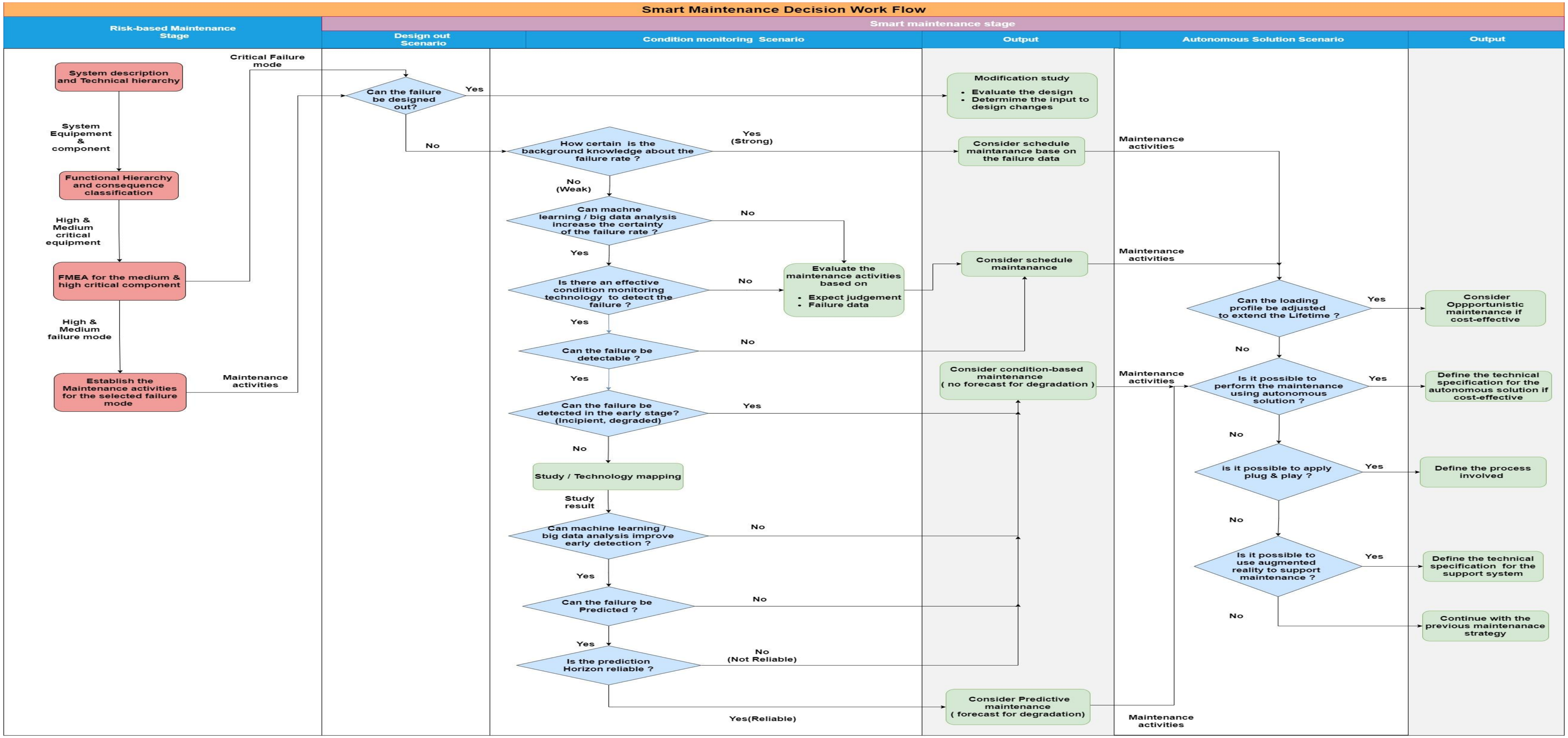


Figure 44. Flowchart answering the research question

The workflow shows the whole procedure adopted in order to achieve the purpose of this research. Meanwhile, some conclusions can be drawn from each procedure.

- Understanding how the system operates and developing the Technical hierarchy proves to be an effective means to initiate the correct maintenance strategy. This study develops the wind turbine taxonomy by grouping the systems, equipment, and maintainable component according to their location to identify where to focus during maintenance activities. Although the previous attempt to develop the wind turbine technical hierarchy has used the standardized taxonomy terminology developed by the Relia wind consortium, this research has presented a new insight using the ISO 144224 standard instead.

- Using the ISO 14224 standard provided a better basis to use the Norsok-Z-008 standard in developing the functional hierarchy and consequence classification. This study created a new list of main functions relating to the wind turbine system, which can be adopted for further research. The risk decision criteria used in consequence classification are not totally valid for offshore wind applications due to the difference in risk-related issues (safety, environment) and other parameters (repair cost, production). Although the results from the criticality classification are based on several assumptions which need to be validated, the drive-train and electrical module equipment seem to be highly critical in the Direct-drive wind turbine.

- This research used the FMEA to identify the critical failure mode, root causes, and risk priority number. This process proves to be effective when assigning maintenance activities. Unlike other research work, this thesis adopted the failure mode style as presented in ISO 14224 standard. The obstacle during this procedure is getting the failure data related to the style of failure mode adopted. However, some assumptions were made which need further verification.

- The thesis has developed a baseline maintenance concept for some wind turbine equipment by defining the maintenance activities and intervals based on the selected failure mode in the FMEA. Though the information obtained, do not cover all equipment because operational data are confidential. However, as shown in table 23, most of the maintenance tasks can be done in the annual maintenance campaign, and the most important discipline for technicians is mechanical. Moreover, the manning for the maintenance task might be overestimated, but this is related to safety issues. Nevertheless, the simulation results confirm that the WT generator has the highest accumulated maintenance time, making it the major cause of downtime for the Direct-drive wind turbine system. Also, this procedure proves to be sufficient when considering maintenance improvements.

- The smart maintenance concept provided the workflow that clearly shows the relevant steps to improve the offshore wind turbine maintenance operation. The verification and validation process conducted makes the workflow reliable and valid. The smart maintenance concept comprises of three scenarios. Implementing the concept will require more information, such as condition monitoring data. Furthermore, implementing just one scenario from the workflow developed is not enough to confirm the overall effectiveness of smart maintenance. Nevertheless, as given in table 31, the implementation of the autonomous solution scenario concludes that the concept might increase wind turbine equipment availability by 39.83%. It can also reduce safety risks associated with maintenance, decrease manning hours by 60.16%, which can be assumed to reduce maintenance costs eventually. In addition, using drones and repair robots for maintenance tasks is not fully automated. It still requires the presence of two technicians due to technical and safety-related issues.

7.1. Research Contribution

This thesis has contributed in the following:

- Provided a new knowledge on implementing a risk-based maintenance approach (based on Norsok-Z-008) for the wind power sector
- Provided a decision workflow for smart maintenance that can be adopted for industrial and academic purposes

References

AkerBP. (2020). *Risk Based Maintenance and Consequence Classification (Additional requirements to Norsok Z-008)*.

Anh, D. T., Dąbrowski, K., & Skrzypek, K. (2018). The Predictive Maintenance Concept in the Maintenance Department of the "Industry 4.0" Production Enterprise. *Foundations of Management, 10*(1), 283-292.

Anylogic. (2021). *Multimethod Simulation Modeling: The benefits of access to different modeling methods*. Retrieved 5 May from https://www.anylogic.com/use-of-simulation/multimethod-modeling/

Arabian-Hoseynabadi, H., Oraee, H., & Tavner, P. (2010). Failure modes and effects analysis (FMEA) for wind turbines. *International Journal of Electrical Power & Energy Systems, 32*(7), 817-824.

Automation, I. (2017). *What is SCADA*. Retrieved 18 April from https://inductiveautomation.com/resources/article/what-is-scada

Bailey, H., Brookes, K. L., & Thompson, P. M. (2014). Assessing environmental impacts of offshore wind farms: lessons learned and recommendations for the future. *Aquatic biosystems, 10*(1), 1-13.

Bernardini, S., Jovan, F., Jiang, Z., Watson, S., Weightman, A., Moradi, P., Richardson, T., Sadeghian, R., & Sareh, S. (2020). A multi-robot platform for the autonomous operation and maintenance of offshore wind farms. *Autonomous Agents and Multi-Agent Systems (AAMAS) 2020*, 1696-1700.

Bhattacharya, S. (2014). Challenges in design of foundations for offshore wind turbines. *Engineering & Technology Reference, 1*(1), 922.

Carroll, J., McDonald, A., Dinwoodie, I., McMillan, D., Revie, M., & Lazakis, I. (2017). Availability, operation and maintenance costs of offshore wind turbines with different drive train configurations. *Wind Energy, 20*(2), 361-378.

Carroll, J., McDonald, A., & McMillan, D. (2016). Failure rate, repair time and unscheduled O&M cost analysis of offshore wind turbines. *Wind Energy, 19*(6), 1107-1119.

Catelani, M., Ciani, L., Galar, D., & Patrizi, G. (2020). Risk Assessment of a Wind Turbine: A New FMECA-Based Tool With RPN Threshold Estimation. *IEEE Access, 8*, 20181-20190.

Christensen, C. (2018a). *Identification and evaluation of innovation opportunities in the operations & maintenance segment of the offshore wind industry* University of Stavanger, Norway].

Christensen, C. (2018b). *Identification and evaluation of innovation opportunities in the operations and maintenance segment of the offshore wind industry* University of stavanger]. https://uis.brage.unit.no/uis-xmlui/handle/11250/2561981

CNBM. (2017). *Offshore Wind Farm Components & Construction Process*. http://www.steelwindtower.com/offshore-wind-farm-components-and-construction-process/

Cognite. (2021). *Smart maintenance: Boost perfomace and uptime by using data proactively*. Retrieved 18 April from https://www.cognite.com/industry-solutions/smart-maintenance

Craig Stout, D. T. (2019). *UAV Approaches to Wind Turbine Inspection Reducing Reliance on Rope-Access*. Retrieved 22 April from https://s3-eu-west-1.amazonaws.com/media.newore.catapult/app/uploads/2019/03/28161605/Cyberhawks-Approach-to-UAV-Inspection-Craig-Stout-ORE-Catapult.pdf

Creswell, J. W. (2014). chapter 1: The selection of research approach In research design: qualitavive, quantitative and mixed methods approaches. https://www.ucg.ac.me/skladiste/blog_609332/objava_105202/fajlovi/Creswell.pdf

Dedecca, J. G., Hakvoort, R. A., & Ortt, J. R. (2016). Market strategies for offshore wind in Europe: A development and diffusion perspective. *Renewable and Sustainable Energy Reviews, 66*, 286-296.

DeepResource. (2017). *Offshore Wind Life Expectancy*. Retrieved 5 May from https://deepresource.wordpress.com/2017/01/07/offshore-wind-life-expectancy/

Deign, J. (2016). *Fully automated drones could double wind turbine inspection rates*. Retrieved 31 January from http://newenergyupdate.com/wind-energy-update/fully-automated-drones-could-double-wind-turbine-inspection-rates

Deveci, M., Özcan, E., John, R., Covrig, C.-F., & Pamucar, D. (2020). A study on offshore wind farm siting criteria using a novel interval-valued fuzzy-rough based Delphi method. *Journal of Environmental Management, 270*, 110916.

Dewan, A., & Asgarpour, M. (2016). *Reference O & M Concepts for Near and Far Offshore Wind Farms*. ECN Petten.

DOD, D. (1980). Military Standard: Procedures for Performing a Failure Mode Effects and Criticality Analysis. *Department of Defense: Washington, DC, USA*.

Dvorak, P. (2016). *Alstom Haliade 150-6MW, first utility-scale wind turbine to work in U.S. waters*. Windpower. Retrieved 25 February from https://www.windpowerengineering.com/alstom-haliade-150-6mw-first-utility-scale-wind-turbine-work-u-s-waters/

El-Thalji, I. (2019). Asset Dynamics Modelling and Simulation: OFF640 Course Compendium.

Energy.gov. (2019). *Advanced Wind Turbine Drivetrain Trends and Opportunities*. Retrieved 16 January from https://www.energy.gov/eere/articles/advanced-wind-turbine-drivetrain-trends-and-opportunities

Equinor. (2019). *The future of offshore wind is a float : Hywind Scotland*. Retrieved 5 January from https://www.equinor.com/en/what-we-do/hywind-where-the-wind-takes-us.html

Equinor. (2021). *Hywind Tampen: the world's first renewable power for offshore oil and gas*. Retrieved 20 January from https://www.equinor.com/en/what-we-do/hywind-tampen.html

Estate, T. C. (2019). *Offshore Wind Operational Report demonstrates strength and maturity of the UK offshore wind industry*. https://www.thecrownestate.co.uk/en-gb/media-and-insights/stories/2020-the-crown-estate-2019-offshore-wind-operational-report-demonstrates-strength-and-maturity-of-the-uk-offshore-wind-industry/

Frederiksen, M. H., & Knudsen, M. P. (2018). Drones for offshore and maritime missions: Opportunities and barriers. *Innovation Fund Denmark*.

Friedrich, K., & Lukas, M. (2017). State-of-the-art and new technologies of direct drive wind turbines. In *Towards 100% Renewable Energy* (pp. 33-50). Springer.

Furevik, B. R., & Haakenstad, H. (2012). Near-surface marine wind profiles from rawinsonde and NORA10 hindcast. *Journal of Geophysical Research: Atmospheres, 117*(D23), n/a. https://doi.org/10.1029/2012JD018523

Gebruers, C. (2015). Safety assessment of offshore O&M access with regard to human resources. *LEANWIND*.

Gerdes, J. (2020). *Using 'Digital Twins' to Boost Production, Cut Costs at Floating Offshore Wind Farms*. Retrieved 29 April from https://www-greentechmedia-com.cdn.ampproject.org/c/s/www.greentechmedia.com/amp/article/using-digital-twins-to-boost-production-reduce-maintenance-at-floating-offshore-wind-farms

Gupta, A., & Bais, A. S. (2020). Offshore Wind Turbine Market. *Global Market Insights*.

Hameed, Z., Hong, Y., Cho, Y., Ahn, S., & Song, C. (2009). Condition monitoring and fault detection of wind turbines and related algorithms: A review. *Renewable and Sustainable Energy Reviews, 13*(1), 1-39.

Hassan, G. G. (2013). *A guide to UK offshore wind operations and maintenance*. Scottish Enterprise.

Hummervoll, L. (2018). *Identification and evaluation of innovation opportunities in operations and maintenance of offshore wind farms* University of Stavanger, Norway].

IEA. (2019). *Offshore Wind Outlook 2019, IEA, Paris*. https://www.iea.org/reports/offshore-wind-outlook-2019

Irawan, C. A., Ouelhadj, D., Jones, D., Stålhane, M., & Sperstad, I. B. (2017). Optimisation of maintenance routing and scheduling for offshore wind farms. *European Journal of Operational Research, 256*(1), 76-89.

IRENA. (2019). *Future of wind: Deployment, investment, technology, grid integration and socio-economic aspects (A Global Energy Transformation paper)* (International Renewable Energy Agency, Abu Dhabi, Issue.

ISO-14224. (2016). Petroleum, petrochemical and natural gas industries — Collection and exchange of reliability and maintenance data for equipment. *BSI Standards Publication*. https://www.iso.org/standard/64076.html#:~:text=ISO%2014224%3A2016%20provides%20a,operational%20life%20cycle%20of%20equipment.

Jon Olson – Siemens, P. B.-M. (2013). *Performance Upgrades of Operational Wind Turbines* https://www.windenergy.org.nz/store/doc/2014NZWEC_PaulBotha_JonOlson.pdf

Jonker, T. (2017). The development of maintenance strategies of offshore wind farm. *Literature assignment ME54010*.

Kahrobaee, S., & Asgarpoor, S. (2011). Risk-based failure mode and effect analysis for wind turbines (RB-FMEA). 2011 North American Power Symposium,

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Langedijk, E. (2016). *Smart Maintenance Management*. maintworld. Retrieved 21 April from https://www.maintworld.com/Asset-Management/Smart-Maintenance-Management

Le, B., & Andrews, J. (2016). Modelling wind turbine degradation and maintenance. *Wind Energy, 19*(4), 571-591.

Lee, K.-H., Jun, S.-O., Pak, K.-H., Lee, D.-H., Lee, K.-W., & Park, J.-P. (2010). Numerical optimization of site selection for offshore wind turbine installation using genetic algorithm. *Current Applied Physics, 10*(2), S302-S306.

Lei, X., Sandborn, P., Bakhshi, R., Kashani-Pour, A., & Goudarzi, N. (2015). PHM based predictive maintenance optimization for offshore wind farms. 2015 IEEE Conference on Prognostics and Health Management (PHM),

Martini, M., Guanche, R., Losada, I. J., & Vidal, C. (2017). Accessibility assessment for operation and maintenance of offshore wind farms in the North Sea. *Wind Energy, 20*(4), 637-656.

Mathiesen, T., Black, A., Grønvold, F., & Alle, P. (2016). Monitoring and inspection options for evaluating corrosion in offshore wind foundations. *NACE Corrosion: Vancouver, CA, Canada*.

McMillan, D., & Ault, G. W. (2010). Techno-economic comparison of operational aspects for direct drive and gearbox-driven wind turbines. *IEEE Transactions on Energy Conversion, 25*(1), 191-198.

Mittelmeier, N., Allin, J., Blodau, T., Trabucchi, D., Steinfeld, G., Rott, A., & Kühn, M. (2017). An analysis of offshore wind farm SCADA measurements to identify key parameters influencing the magnitude of wake effects. *Wind Energy Science, 2*(2), 477-490.

Musial, W., & Butterfield, S. (2004). *Future for offshore wind energy in the United States*.

NORSOK-Z-008. (2001). Criticality analysis for maintenance purposes. *Norwegian Technology Centre*.

Odin, M. (2021). *Master Thesis discussion: Information about maintenance activities for wind turbine* [Interview].

Osmanbasic, E. (2020). *The Future of Wind Turbines: Comparing Direct Drive and Gearbox*. Retrieved 14 January from https://www.engineering.com/story/the-future-of-wind-turbines-comparing-direct-drive-and-gearbox

Paramor, O., Allen, K., Aanesen, M., Armstrong, C., Piet, G., van Hal, R., van Hoof, L., & van Overzee, H. (2009). MEFEPO North Sea Atlas.

Pérez, P., Fausto Pedro García Márquez a, b, A. T., & Papaelias, M. (2013). Wind turbine reliability analysis. *Energy Rev*, 463-472.

Pillay, A., & Wang, J. (2003). Modified failure mode and effects analysis using approximate reasoning. *Reliability Engineering & System Safety, 79*(1), 69-85.

Porter, M. E., & Heppelmann, J. E. (2014). How smart, connected products are transforming competition. *Harvard business review, 92*(11), 64-88.

Priyanta, D., & Zaman, M. (2021). The development of a risk-based maintenance flowchart to select the correct methodology to develop maintenance strategies of oil and gas equipment. IOP Conference Series: Materials Science and Engineering,

Ramírez, L., Fraile, D., & Brindley, G. (2020). Offshore wind in Europe: Key trends and statistics 2019.

Reder, M. D., Gonzalez, E., & Melero, J. J. (2016). Wind turbine failures-tackling current problems in failure data analysis. Journal of Physics: Conference Series,

Ribrant, J. (2006). Reliability performance and maintenance-a survey of failures in wind power systems. *KTH school of Electrical Engineering*, 59-72.

Ribrant, J., & Bertling, L. (2007). Survey of failures in wind power systems with focus on Swedish wind power plants during 1997-2005. 2007 IEEE power engineering society general meeting,

Scheu, M. N., Tremps, L., Smolka, U., Kolios, A., & Brennan, F. (2019). A systematic Failure Mode Effects and Criticality Analysis for offshore wind turbine systems towards integrated condition based maintenance strategies. *Ocean Engineering, 176*, 118-133.

Selbyville, D. (2020). *The offshore wind turbine market value from floating installation segment will witness 80% growth through 2026 driven by growing saturation of nearshore offshore sites coupled with increasing demand for high operational capacity utilization.* Retrieved 7 Janunary from https://www.globenewswire.com/news-release/2020/07/14/2061657/0/en/Offshore-Wind-Turbine-Market-worth-USD-21-Bn-by-2026-Global-Market-Insights-Inc.html

Seyr, H., & Muskulus, M. (2019). Decision support models for operations and maintenance for offshore wind farms: A review. *Applied Sciences, 9*(2), 278.

Sglunda, R. (2016). Predictive Maintenance 4.0 Knowledge. *Maintworld*. https://www.maintworld.com/Asset-Management/Predictive-Maintenance-4.0-Knowledge

Shafiee, M., & Dinmohammadi, F. (2014). An FMEA-based risk assessment approach for wind turbine systems: a comparative study of onshore and offshore. *Energies, 7*(2), 619-642.

Shafiee, M., Zhou, Z., Mei, L., Dinmohammadi, F., Karama, J., & Flynn, D. (2021). Unmanned Aerial Drones for Inspection of Offshore Wind Turbines: A Mission-Critical Failure Analysis. *Robotics, 10*(1), 26.

Sheppard, R. E., Puskar, F., & Waldhart, C. (2010). SS: Offshore Wind Energy Special Session: Inspection Guidance for Offshore Wind Turbine Facilities. Offshore Technology Conference,

Siemens-Gamesa. (2021). A clean energy solution – from cradle to grave. https://www.siemensgamesa.com/en-int/-/media/siemensgamesa/downloads/en/products-and-services/offshore/brochures/siemens-gamesa-environmental-product-declaration-epd-sg-8-0-167.pdf

Slengesol, I., De Miranda, W. P., Birch, N., Liebst, J., & van der Herm, A. (2010). Offshore wind experiences: a bottom-up review of 16 projects. *Tec Rep*.

Sohoni, V., Gupta, S., & Nema, R. (2016). A critical review on wind turbine power curve modelling techniques and their applications in wind based energy systems. *Journal of Energy, 2016*.

SPARTA. (2018). System Performance, Availability and Reliability Trend Analysis. *SPARTA 2017/18 Portfolio Review*

SPARTA. (2019). *System Performance, Availability and Reliability Trend Analysis – Portfolio Review 2018/19*.

Staoil. (2015). Hywind Scotland Pilot Park : Environmental Statement Non Technical summary.

Stetco, A., Dinmohammadi, F., Zhao, X., Robu, V., Flynn, D., Barnes, M., Keane, J., & Nenadic, G. (2019). Machine learning methods for wind turbine condition monitoring: A review. *Renewable energy, 133*, 620-635.

Task, I. W. T. (2017). Wind farm data collection and reliability assessment for O&M optimization.

Tavner, P. (2012). *Offshore wind turbines: reliability, availability and maintenance* (Vol. 13). IET.

Tavner, P., Van Bussel, G., & Spinato, F. (2006). Machine and converter reliabilities in wind turbines. 127 - 130.

Vagle, G. (2018). *Is your company ready for digitalization?* University of stavanger]. Uis brage. https://uis.brage.unit.no/uis-xmlui/bitstream/handle/11250/2562601/Vagle_Gaute.pdf?sequence=1&isAllowed=y

Van Bussel, G., Henderson, A., Morgan, C., Smith, B., Barthelmie, R., Argyriadis, K., Arena, A., Niklasson, G., & Peltola, E. (2001). State of the art and technology trends for offshore wind energy: operation and maintenance issues. Offshore Wind Energy EWEA special topic conference,

Van Bussel, G., & Zaaijer, M. (2001). Reliability, availability and maintenance aspects of large-scale offshore wind farms, a concepts study. Proceedings of MAREC,

Van Haaren, R., & Fthenakis, V. (2011). GIS-based wind farm site selection using spatial multi-criteria analysis (SMCA): Evaluating the case for New York State. *Renewable and Sustainable Energy Reviews, 15*(7), 3332-3340.

Appendices

Appendix A. Interview questions and answers

As specified in the data collection chapter section 4.2, only two target candidates responded to the interview question. Therefore, the answers to the question from the two responses are presented in the table below.

Relevant topics	**Questions**	**Answers**	
		An employee from Siemens Gamesa	**Project manager from Espeland Energi AS**
Inspection operation	**1. How many Inspection campaigns per year for offshore wind turbine**	One inspection campaign per year	One inspection campaign per year. However, wind farm owners demand two inspection campaign per year
	2. Is there an inspection campaign for specific equipment in the wind turbine	Wind turbine blade inspection, foundation inspection	In some cases, there is a separate inspection campaign from the wind turbine blade
	3. What is the specific purpose for each inspection operation	The result from the inspection helps to plan the maintenance activities to be carried out in the maintenance campaign	**Service Inspection Interval:** Between (March-May): The main purpose is to map out any problem or fault that might have occurred during the winter and prepare for repair in the summertime Between (September – October): The main purpose is to check if the maintenance repair done in the summer are still okay
	4. What equipment is to be inspected in the turbine (external and internal)	Equipment inside the nacelle and down the tower	Mainly all equipment inside the nacelle
	5. What other activities happen during the inspection operation	X	During the Inspection, some basic maintenance activities can be performed, e.g., cleaning, tightening of bots
Maintenance operation	**7. How many planned maintenance campaigns per year**	Annual maintenance campaign. In some cases, maintenance is carried out based on the alert from the condition monitoring system	Annual maintenance campaign (once in the summer months)
	8. what are the typical task/ activities during each maintenance	Depending on the equipment, Cleaning, function test, greasing, oil change.	**Main activities include**: Major repairs and Minor repairs or replacement based on the report from the service inspection campaign (March-May)

Appendix B. Technical Hierarchy Worksheet

Technical Hierarchy of the Direct-drive Wind Turbine (ISO 14224 Standard)

Taxonomy level	Plant/Unit	Section/System	Equipment Unit	Subunit	Component	Admin tag	Tag no
4	**Wind Turbine**						
5		**20- Rotor Module**					20-00-00
6			Rotor Hub				20-10-00
7				Hub		20-10-HB	
6			Pitch system				20-11-00
7				Pitch cabinet		20-11-CB	
8					Battery		20-11-CB-B001
8					Battery charger		20-11-CB-B002
8					Pitch controller		20-11-CB-C001
8					Heater		20-11-CB-H001
7				Pitch drive		20-11-PD	
8					Pitch motor		20-11-PD-M001
8					Pitch Motor Encoder		20-11-PD-M002
8					Pitch gearbox		20-11-PD-G001
8					Air Brake		20-11-PD-A001
8					Position Encoder		20-11-PD-E001
8					Pitch lube pump		20-11-PD-L001
8					Valves		20-11-PD-V001
6			Blade 1				20-12-00
6			Blade 2	-			20-13-00
6			Blade 3	-			20-14-00
5		**21-Drive train Module**					21-00-00
6			Generator				21-10-00
7				Rotor		21-10-RT	
7				Stator		21-10-ST	
7				Sensors		21-10-SS	
8					Temperature sensor		21-10-SS-T001
8					Encoder		21-10-SS-E001
8					Wattmeter		21-10-SS-W001
7				Generator Lubrication subunit		21-10-GL	
8					Pump		21-10-GL-P001
8					Pressure sensor		21-10-GL-P002
8					Reservoir		21-10-GL-R001
8					Valves		21-10-GL-V001
7				Generator cooling subunit		21-10-GC	
8					Cooling fan		21-10-GL-C001
8					Filter		21-10-GC-F001
8					Hose		21-10-GC-H001
8					Radiator		21-10-GC-R001
6			Main shaft set				21-11-00
7				Low-speed side		21-11-LS	
8					Main bearing temperature sensor		21-11-LS- M001

7				Sensors		21-11-SS	
8					Low speed side sensor		21-11-SS-S001
6			Brake				21-12-00
8					Brake sensor		21-12-00-B001
5		**22- Eletriacal Module**					22-00-00
6			Converter				22-10-00
7				Coverter power bus		22-10-CB	
8					capacitor		22-10-CB-C001
8					Power contactors		22-10-CB-C002
8					Load switch		22-10-CB-S001
8					Inductor		22-10-CB-I001
8					Pre-charge unit		22-10-CB-P001
7				Power conditioning		22-10-PC	
8					Line Filter		22-10-PC- F001
8					Voltage limiter unit		22-10-PC-V001
8					Switchgear		22-10-PC-S001
6			Power electrical system				22-11-00
7				Power circuit		22-11-PC	
8					Cables		22-11-PC-C001
8					Machine contactor		22-11-PC-C002
8					Mv Busbar/isolator		22-11-PC-B001
6			Control & Communication system				22-12-00
7				Condition monitoring subunit		22-12-CM	
8					Sensors		22-12-CM-S001
8					Condition cable		22-12-CM-C001
8					Data logger		22-12-CM-D001
7				Controller hardware		22-12-CH	
8					Controller Power supplier		22-12-CH-P001
7				Communication system		22-12-CS	
8					Field Bus Master		22-12-CS-F001
8					Field Bus slave		22-12-CS-F002
8					Frequency unit		22-12-CS-F003
7				Ancillary equipment		22-12-AE	
8					Breaker		22-12-AE-B001
8					Cabinet Temperature sensor		22-12-AE-S001
8					Cable		22-12-AE-C001
8					Contactor		22-12-AE-C002
5		**23-Nacelle Module**					23-00-00
6			Nacelle				23-10-00
6			Yaw system				23-11-00
7				Yaw drive		23-11-YD	
8					Yaw motor		23-11-YD-M001
8					Yaw Ring		23-11-YD-R001
8					Yaw gearbox		23-11-YD-G001
7				Yaw sensor		23-11-YS	
8					Yaw encoder		23-11-YS-E001

8					Wind-up counter		23-11-YS-W001
7				Yaw brake		23-11-YB	
					Brake		23-11-YB-B001
6			Hydraulics system				23-12-00
7				Actuators		23-12-AT	
8					Cylinder		23-12-AT-C001
8					Position controller		23-12-AT-C002
8					Hose		23-12-AT-H001
8					Limit switch		23-12-AT-S001
7				Hydraulic power pack		23-12-HP	
8					Motor		23-12-HP-M001
8					Pump		23-12-HP-P001
8					Pressure valve		23-12-HP-P002
8					Filter		23-12-HP-F001
6			Nacelle auxiliaries				23-13-00
7				Safety systems		23-13-SS	
8					Safety crane		23-13-SS-C001
8					Lightening protection		23-13-SS-L001
7				Meterological sensor		23-13-MS	
8					Wind vane		23-13-MS-W001
8					Anemometer		23-13-MS-A001
5		**24- Sturucture support**					24-00-00
6			Tower				24-10-00
7				Tower		24-10-TW	
8					Climb assist		24-10-TW-A001
8					Tower section		24-10-TW-T001
7				Access equipment		24-10-AE	
8					Landing pad		24-10-AE-L001
8					Ladder		24-10-AE-L002
8					Lightning protection		24-10-AE-L003
6			Foundation				24-11-00
7				Monopile		24-11-MP	
8					Pile		24-11-MP-P001
8					Corrosion protection		24-11-MP-P002
8					Transition piece		24-11-MP-T001

Functional Hierarchy of the Offshore wind turbine

Main system	System/Section	Main function (MF)	Sub-function	Function Description	Consequence classification					Criticality
					Safety	Environment	Repair cost	Production	Frequency	
Wind Turbine										
	Rotor Module									
		Wind catching		Harversting wind by the blade	6	6	4	3	4	H
			MAIN		MF	MF	MF	MF	MF	H
		Angle positioning		Action done by the pitch system	6	6	5	5	4	M
			MAIN	Main task	MF	MF	MF	MF	MF	M
			ALARM	Monitoring	6	6	6	5	4	M
			CONTROL	Regulating the pitch rotation	MF	MF	MF	MF	MF	M
			IND	Local Indicator	6	6	6	5	3	M
	Drive train Module									
		Transfering		Transfer mechanical energy to the generator	6	6	4	3	3	H
			MAIN	Transfering	MF	MF	MF	MF	MF	H
			ALARM	Monitoring	6	6	5	6	3	L
		Generating		Produce electricity	6	6	3	3	4	H
			MAIN	Generating power	MF	MF	MF	MF	MF	H
			ESD	Emergency shutdown	6	6	4	MF	2	M
			ALARM	Monitoring	6	6	5	5	3	M
			IND	Local Indicator	6	6	5	6	3	M
		Lubricating		Lubricating the generator	6	6	4	4	3	M
			MAIN	Main task	MF	MF	MF	MF	MF	M
			PSV	Safety equipment for pressure relief	6	6	4	4	3	M
			ALARM	Monitoring	6	6	5	6	3	M
			CONTROL	Regulating	MF	MF	MF	MF	MF	M
			PSD	Process shutdown	6	6	4	4	3	M
		Cooling		cooling the generator	6	6	4	4	3	M
			MAIN	cooling	MF	MF	MF	MF	MF	M
			CONTROL	Regulating	MF	MF	MF	MF	MF	M
		Braking		Speed reduction	6	6	4	3	4	H
			MAIN		MF	MF	MF	MF	MF	H
			ESD	Emergency shutdown	6	6	4	4	3	M
			CONTROL	Regulating	MF	MF	MF	MF	MF	H
	Electrical system									
		Frequency Coverting			6	6	4	3	4	H
			MAIN	Coverting	MF	MF	MF	MF	MF	H
			ALARM	Monitoring	6	6	5	6	3	M
			CONTROL	Regulating	MF	MF	MF	MF	MF	H

			IND	Local Indicator	6	6	5	6	2	L
		Monitoring		Monitoring the system condition	6	6	5	5	4	M
			MAIN		MF	MF	MF	MF	MF	M
			CONTROL	Regulating	MF	MF	MF	MF	MF	M
			ALARM	Monitoring	6	6	5	6	2	L
			PSD	Process shutdown	6	6	4	MF	3	M
		Distributing		Distributing power to control equipments	6	6	4	4	3	M
			MAIN	Distributing	MF	MF	MF	MF	MF	M
	Nacelle module									
		Housing		Housing the turbine components	6	6	3	4	2	M
			MAIN		MF	MF	MF	MF		M
		Turbine head rotation		Action done by the yaw system	6	6	4	4	3	M
			MAIN	Rotating	MF	MF	MF	MF	MF	M
			CONTROL	Regulating	MF	MF	MF	MF	MF	M
			ALARM	Monitoring	6	6	5	6	2	L
		Transmitting		Transmitting energy for motion	6	6	4	4	3	M
			MAIN	Transmitting	MF	MF	MF	MF	MF	M
			PSD	Process shutdown	6	6	4	MF	3	M
			CONTROL	Regulating	MF	MF	MF	MF	MF	M
			PSV	Pressure relief valve	6	6	4	4	3	M
		Braking		Regulating the speed of yaw rotation	6	6	4	4	3	M
			MAIN		MF	MF	MF	MF	MF	M
			CONTROL	Regulating	MF	MF	MF	MF	MF	M
	Structure Support									
		Load supporting		Holds the Turbine	6	6	3	3	2	M
			MAIN		MF	MF	MF	MF	MF	M

Appendix D. FMEA Worksheet

Failure Mode Effects Analysis (FMEA)

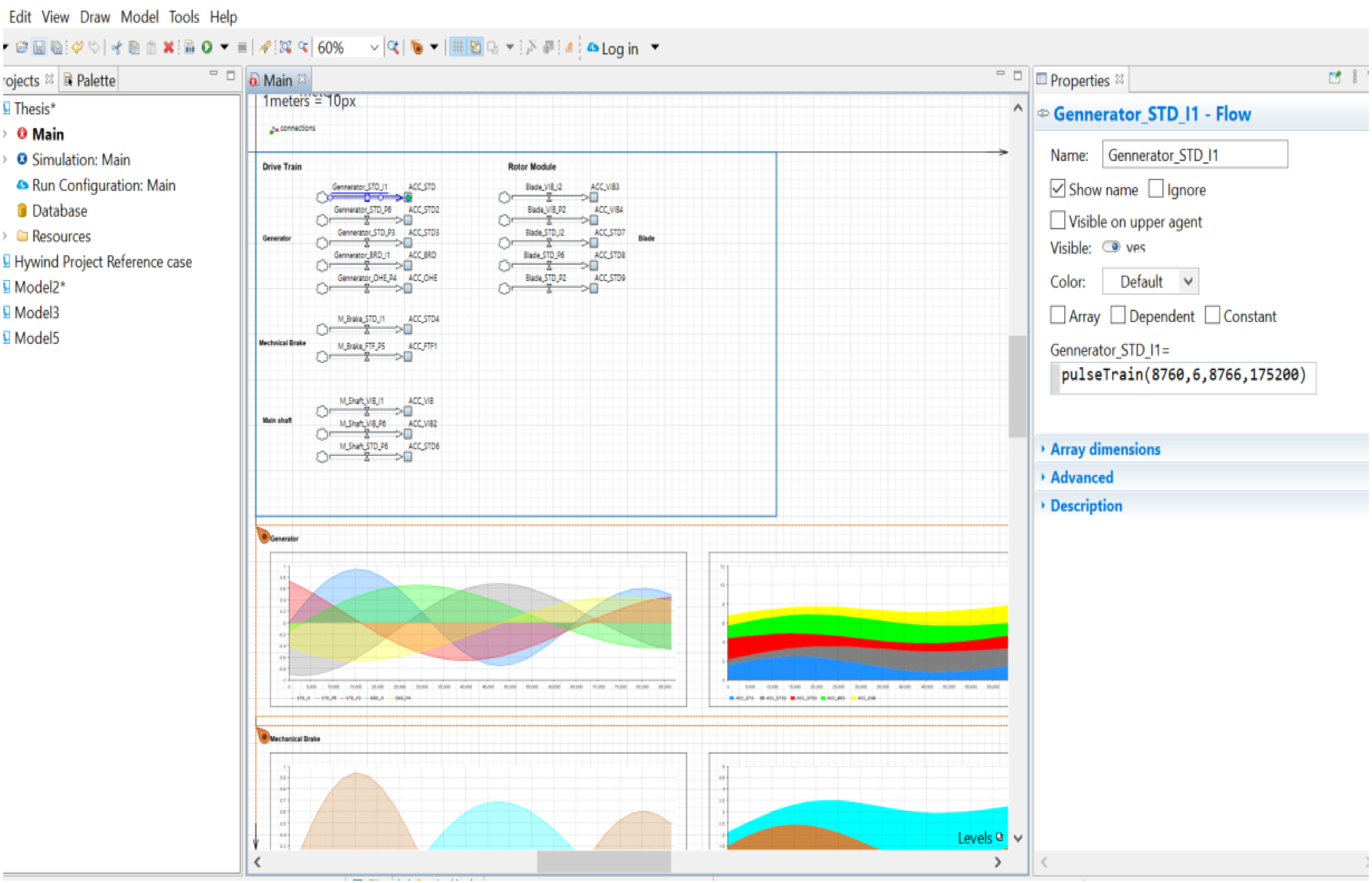
OWNER: Udoh Francis Makua

FMEA Workshop
Wind Turbine system(Direct Drive)

Date:
Year: 2021

Wind Turbine system/section	Equipment unit	Main Funcition	Potential Failure Mode	Local Failure effect	Global failure effect	Severity (S)	Potential Root cause	occurrence (O)	Current Controls	Detection (D)	RPN	Recommended action	Action taken	SEV	OCC	DET	RPN
What system is to Investigated	What are the Equipment in the sytem	What is the Function of the Equipment.	In what way can the function fail	What is the impact of the function failure on the system	What is the impact of the function failure on the system, process, costomer and regulation	How severe is the effect	What causes the function to fail	How frequent does the Failure mode occur	What are the existing controls/ procedures to prevent the failure mode the root cause	How possible can the cause or failure be detected	Risk priority number (Given by S*O*D)	What can be done to reduce failure and increase detetion	What are the action taken				
Rotor Module																	
	Pitch system	The rotor pitch system is generally located inside the rotor hub. The pitch is helps in angle positioning of the blade toward the wind for effective energy catching	**FTR**	Uncontrolled blade pitching	Lost of efficiency of the turbine	3	Controller failure/malfunction, wearing of pitch gear	3	Coprehensive inspection operation and maintenance proceudre should be strictly adhere to. Comprehensive inspection inspection procedure. New Design specification for the components.	4	36			3	3	4	36
			STD	Unable to to operate properly due wearing of the gears	Lost efficiency	3	Material fatique, Corrosion and cracks and insuficient lubrication	3		7	63			2	3	7	63
			OHE	Deterioration/damage to the pitch controller	Loss of efficiency	3	Electrical overload/ insulation failure	3		7	63			2	3	7	63
			AIR	low or too high wind capture	Lost efficiency	3	Fabrication error/ sensor failure	3		4	36			2	3	4	36
	Blade	The blades are attached to the rotor hub. The function of the blade is for wind catching to enable the whole process	**VIB**	Increase d mechanical load	Lost of efficiency	3	High wind speed and delamination	3		4	36			2	3	4	36
			FRO	loss of energy production	Shutdown of the single turbine	3	Mechanical wear of the blade root couplings	3		4	36			3	3	4	36
			STD	Unable to capture enough wind	Reduced total power production	4	Material fatique, Corrosion and cracks	3		4	48			2	3	4	48
Drive-Train Module																	
	Main shaft	For the Direct-drive wind turbine, the main shaft is located between the rotor and the generator and it is been supported by the main bearing. It is responsible for transfering mechanical energy	**STD**	Increased fatigue and vibration to attached system components	lost efficiency of the turbine	3	Material fatique	3	The maintenance procedure contained in the manual or as specified by the OEM should be strictly adhere to. Comprehensive inspection inspection procedure. Design modification for the component	7	63			2	3	7	63
			VIB	Increased machnical load for the connected components	lost efficiency/ full stop single turbine	2	Insufficient material quality	3		7	42			2	3	7	42
	Mechnical Brake	The brake system is connetec to the shaft in order to reduce the rotational speed during high speed condition or during emergcy shut-down of the system	**STD**	Increased fatigue and vibration to attached system components	Lost efficiency	3	Mechanical wear	3		7	63			2	3	7	63
			BRD	Damage to other component due to uncontrolled rotational speed	Full stop single wind turbine	4	Design fault/ Aging material	2		7	56			3	2	7	56
			FTF	Damage to the generator due to overloading	Full stop single wind turbine	4	Control Failure	2		7	56			3	2	7	56
	Generator	The generator is the power equipment in the turbine. It converts the mechanical energy from the shaft to electrical energy. For the Direct-drive turbine, the generator has several permanent magnet which aid to achieve the desire output voltage	**LOO**	Inadeqaute power production	Unable to integrate with the grid	3	Electrical overload/ Winding failure	3		4	36			2	3	4	36
			STD	Increased fatigue and vibration to attached system components	Lost efficiency	3	Material wear	4		7	84			2	4	7	84
			NOI	Noise pollution / increased compoent degreadation	Noise pollution	3	Loosen parts	3		4	36			2	3	4	36
			BRD	Unable to generate power	Loss of power generation single turbine	4	Material defect	3		7	84			3	3	7	84
			OHE	Damage to the generator component	Full stop single turbine	4	Electrial overload/ insufficient cooling	5		4	80			3	5	4	80
Electrical Module																	
	Converter	The function of the Converter is to enable variable frequency conversion from the generator output to make it appropraite for the grid or load	**AIR**	Inadequte control due to false signal	Lost efficiency	2	Sensor Malfunction	3	The maintenance procedure contained in the manual or as specified by the OEM should be strictly adhere to. Comprehensive inspection inspection procedure. Design modification for the component	7	42			2	3	7	42
			FTR	Unable to regular power output	Full stop single turbine	3	control failure	3		7	63			3	3	7	63
			OHE	Damage to electronic components	Lost efficiency	3	Electrical overload	3		4	36			3	3	4	36
			PDE	Improper operation of electronic component due to false alarm	Lost efficiency	3	Fabrication error	3		4	36			2	3	4	36
	Control system	The control system is the brain of the Turbine. It is connected to several sensors within the turbine and controls the pitch, generator, yaw and other component in the turbine. It monitors the general performance of the the wind turbine sysetm.	**AIR**	Loss of control of due to false signal	Lost efficiency	3	Sensor Malfunction	3		7	63			2	3	7	63
			PDE	Improper operation of electronic component due to false alarm	Lost efficiency	2	Sensor Malfunction	5		7	70			2	5	7	70
			FTR	Unable to regulate performance of the turbine system	Lost efficiency/ Full stop wind turbine	3	Control failure	5		4	60			3	5	4	60
			DOP	Temporary unavailability of monitoring function	Lost efficiency	3	Loss of power input	5		4	60			3	5	4	60
	Power Electrical system	The power electrical system consisit of the power cables, isolators and contactors. It is responsible for transmitting of power from the genetator to the grid	**STD**	Poor power transmission	Reduction of Wind turbine efficiency	4	Material defect	3		4	48			2	3	4	48
			OHE	Damage to cable insulation and short circuit fault	Lost efficiency	3	Electrical short	5		4	60			2	5	4	60
			LOO	Inadequate power supply to connected device	Loss efficiency	3	Electrical Overload	3		4	36			2	3	4	36
Nacelle Module																	
	Yaw system	The yaw system is located between the rotate head and the turbine tower. It consist of bearing, sensors and motor to ensure the wind turbine is producing the maximum electricity by facing the rotor towards the wind direction	**FRO**	Reduced wind harvesting inability to rotate turbine head	Loss output power/ Loss efficiency	3	Failed couplings and sensor function failure	3	The maintenance procedure contained in the manual or as specified by the OEM should be strictly adhere to.	4	36			3	3	4	36
			STD	Increased fatigue and vibration to attached system components	Loss efficiency	3	Vibration fatigue	3		4	36			2	3	4	36
			BRD	Total failure to rotate the turbine head	Loss efficiency / Full stop single turbine	3	Degraded / undesired sensor error	3		4	36			3	3	4	36
			FTR	Unable to regulate the the rotational load	Loss efiiciency	3	Sensor Malfunction	3		4	36			2	3	4	36

Appendix E. Anylogic maintenance Taks Simulation



Gennerator_STD_I1 - Flow

Name: Gennerator_STD_I1

☑ Show name ☐ Ignore

☐ Visible on upper agent

Visible: yes

Color: Default

☐ Array ☐ Dependent ☐ Constant

Gennerator_STD_I1=

```
pulseTrain(8760,6,8766,175200)
```