Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Mechanical and Industrial Engineering

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Maintenance Optimization of offshore wind farms using digital technologies and criticality assessment

Techniques for achieving sustainability

Master's thesis in RAMS
Supervisor: Per Schjølberg
Co-supervisor: Harald Rødseth
June 2023

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Preface

This master's thesis was carried out by Nourhan Alzammar, a RAMS student at NTNU. The thesis was conducted for the Norwegian University of Science and Technology (NTNU). It counts as 30 credits and is a requirement for the subject TPK4950, spring semester of 2023.

The thesis was written with guidance from the main supervisor Per Schjølberg from NTNU and co-supervisor Harald Rødseth from Oceaneering AS.

The topic of the thesis is "Maintenance Optimization in offshore wind farms using digital technologies and criticality assessment: Techniques for achieving sustainability". It has been worked to give a detailed study about the challenges that hinder offshore wind farms to attain sustainability, and how digital technologies and criticality assessment contribute to addressing these challenges by optimizing maintenance planning based on anomaly degree (AD) assessment and profit loss indicator (PLI) estimation. The integration of criticality assessment and PLI estimation can be promising future tools for an improved working environment in offshore wind farms.

This report is written for master students and readers who are curious in understanding the contribution of both digital technologies and the criticality assessment in achieving sustainability

Nourhan Alzammar
08.06.2023
Trondheim

Acknowledgment

My gratitude goes to the main supervisor, Per Schjølberg, for providing his valuable insights and guidance throughout this thesis. I am equally grateful to co-supervisor, Harald Rødseth, for his contributions and support through his plenitude knowledge and experience. I cannot measure the quality of materials received from both supervisors and I, therefore, say a huge thanks to them.

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I extend my gratitude to the Oceaneering company and Oceaneering teams who always supported me. I am highly proud to collaborate with the Oceaneering family.

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Moreover, I would lovely extend my pleasure and gratitude to my husband, my children, my mother, and my best friend Hilde for their patience, constant support, understanding , and encouragement to do my best. Their contribution is priceless.

I would thank everyone at NTNU who helped me and guided me to write this report. I am truly grateful for your presence in my academic journey.

Summary

Since wind power forms the backbone of sustainable energy systems, and has attractive characteristics such as availability and relatively low environmental footprint, offshore wind farms (OWFs) have developed rapidly, and have increasingly deployed offshore. This causes the operation and maintenance of wind turbines to become more challenging and costly. Furthermore, increased energy potential, O&M operator safety, and environmental considerations also become more prominent issues that should be considered in order to achieve sustainability in the offshore wind sector. With technological advancements, the digitalization of maintenance services could contribute to optimizing performance, increasing safety, decreasing environmental impacts, and reducing operational and maintenance costs. The aim of this research is to examine how digitalization and advanced analytics contributes to optimizing maintenance planning in order to achieve sustainability in offshore wind farms based on anomaly degree (AD) assessment and profit loss indicator (PLI) estimation and criticality assessment. The results have highlighted that the integration of criticality assessment and PLI estimation provides an evaluation of critical components with the potential impact of failures, and financial consequences associated with maintenance decisions. This enables operators to make informed decisions regarding prioritizing maintenance activities, resource allocation, and risk management. It is concluded that the integration of criticality assessment and PLI estimation could be promising tools used for an improved working environment in offshore wind farms. Therefore, more investigations with case studies should be done to explore the impact of the implementation of criticality assessment and PLI estimation in real-world offshore wind farm operations.

Sammendrag

Siden vindkraft utgjør ryggraden i bærekraftige energisystemer, og har attraktive egenskaper som tilgjengelighet og relativt lavt miljøavtrykk, har havvindparker (OWF) utviklet seg raskt, og har i økende grad blitt distribuert til havs. Dette fører til at drift og vedlikehold av vindturbiner blir mer utfordrende og kostbart. Videre blir økt energipotensial, driftssikkerhet og miljøhensyn også mer fremtredende problemstillinger som bør vurderes for å oppnå bærekraft i havvindsektoren. Med teknologiske fremskritt kan digitalisering av vedlikeholdstjenester bidra til å optimalisere ytelsen, øke sikkerheten, redusere miljøpåvirkningen og redusere drifts- og vedlikeholdskostnader. Målet med denne forskningen er å undersøke hvordan digitalisering og avanserte analyser bidrar til å optimalisere vedlikeholdsplanlegging for å oppnå bærekraft i offshore vindparker basert på anomaligrad (AD) vurdering og profit loss indicator (PLI) estimering og kritikalitetsvurdering. Resultatene har fremhevet at integrasjonen av kritikalitetsvurdering og PLI-estimering gir en evaluering av kritiske komponenter med potensiell innvirkning av feil, og økonomiske konsekvenser knyttet til vedlikeholdsbeslutninger. Dette gjør det mulig for operatører å ta informerte beslutninger angående prioritering av vedlikeholdsaktiviteter, ressursallokering og risikostyring. Det konkluderes med at integrering av kritikalitetsvurdering og PLI-estimering kan være lovende verktøy som brukes for et forbedret arbeidsmiljø i havvindparker. Derfor bør flere undersøkelser med case-studier gjøres for å utforske virkningen av implementeringen av kritikalitetsvurdering og PLI-estimering i virkelige offshore-vindparkoperasjoner.

Acronyms

IoT Internet of Things

AI Artificial intelligence

LCOE Levelized cost of energy

CapEx Capital expenditure

OpEx Operational expenditure

DecEx Decommissioning expenditure

OWT Offshore wind turbines

OWFs Offshore wind farms

ML Machine learning

KPI Key Performance Indicator

PLI Profit loss indicator

O&M Operation and maintenance

RUL Remaining Useful Life

AD Anomaly degree

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Chapter 1

Introduction

With the gradual depletion of fossil fuels and the harmful effects of carbon emissions on the environment, many efforts are being made to adopt renewable energy sources as alternatives to fossil fuels in order to address climate change and move towards a sustainable and low-carbon future (Li et al., 2022). In recent years, Offshore wind farms have emerged as a promising source of sustainable and emission-free energy production due to a high level of technological readiness and abundant wind resources where they are located away from populated areas, maximizing energy generation possibilities (Ren et al., 2021). However, ensuring the long-term sustainability, safe and profitable systems, and efficient performance of offshore wind farms demands effective maintenance planning and management in the face of the challenges posed by their harsh and operationally demanding environments (Xia & Zou, 2023). According to statistical data, O&M costs form up to 25–30% of the total investment cost of an offshore wind project (Xia & Zou, 2023). To transition to a more sustainable energy system, it is necessary to take appropriate measures that aim to decrease O&M costs and maximize the availability, and economic benefits of offshore wind energy while minimizing negative impacts on the economy, society, and surrounding environment (Xia & Zou, 2023). Maintenance plays a crucial role in effective asset management. By adopting preventive maintenance types, offshore wind farm organizations can optimize the utilization and performance of assets. According to (Golysheva, 2021), adopting predictive maintenance in offshore wind farms can provide more oversight and control of O&M schedules, as well as savings of 30% from O&M budgets. With advanced digital technologies used in predictive maintenance like sensors, big data analytics, and artificial intelligence techniques, maintenance planning can be more positive in offshore wind farms (Haghshenas et al., 2023; Xia & Zou, 2023). These digital technologies contribute to monitoring the real-time conditions of components and detecting deviations from normal operating conditions that cause components breakdown and affect safety and economics (Xia & Zou, 2023). This enables operators to determine critical components/turbines and prioritize maintenance activities based on the severity of anomalies, as well as make informed decisions regarding repairs or replacements. Furthermore, the use of profit loss indicator (PLI) estimation in criticality assessment for offshore wind farms, PLI having proven its efficiency in other fields, can assist in improving the decision-making process in maintenance planning. PLI estimation can evaluate the potential financial indicators such as production losses, repair costs, and revenue impacts associated with component failures. This estimation helps operators to identify critical components that require significant financial (Okafor, 2022). Thus enhancing maintenance planning efficiency, optimizing resource allocation, and minimizing financial losses.

Despite the use of digitalization and advanced analytics techniques for maintenance planning of offshore wind farms in order to reduce maintenance cost, optimize the operation and maintenance of offshore wind farms, and improve logistics. As of now, there is still a significant gap in clarifying the impact of digitalization on maintenance from a sustainability perspective. Therefore, this research is to examine how digitalization and advanced analytics contributes to optimizing maintenance planning in order to achieve sustainability in offshore wind farms based on principles-based anomaly degree assessment and PLI estimation and criticality assessment.

1.2 Research questions

The research problem revolves around the need to investigate and analyze the role of criticality assessment and PLI estimation in maintenance planning for offshore wind farms, with a specific focus on their impact on achieving sustainability objectives. The problem involves also clarifying the role of digital technologies in improving maintenance strategies. This thesis provides answers to the following questions:

- How do digital technologies contribute to improving maintenance planning and enhancing sustainability in offshore wind farms?
- What are the benefits and limitations associated with the utilization of digital technologies in offshore wind farm?

- How do criticality assessment and PLI estimation contribute to improving maintenance planning in offshore wind farms?
- What is the impact of criticality assessment and PLI estimation on enhancing sustainability in offshore wind farms?
- What are the benefits and limitations associated with the utilization of criticality assessment and PLI estimation in offshore wind farm maintenance planning?
- What is the future of offshore wind farms? and how will maintenance be carried out in the future?

1.3 Limitations

This thesis focuses on the maintenance optimization of offshore wind farms by using both digital technologies and criticality assessment including PLI estimation in order to achieve sustainability. This report was written as theoretical research since there was limited literature about offshore wind farms as well as a lack of data to analyze and discover the contribution of advanced technologies in optimizing maintenance. I contacted El-Watch AS for information and data on the matter. They were very collaborative, and gave me valuable insight and information into how IoT sensors can assist in maintenance, and presented me with the different types of robust sensors. Unfortunately, El-Watch AS had not been involved in installing sensors in offshore wind farms or onshore yet. Therefore, it was no data to analyze. Furthermore, I tried to use theories from other fields to explain the importance of adapting PLI estimation in offshore wind farms, and how can contribute to improving the decision-making process in maintenance planning.

1.4 Approach

A comprehensive review of existing literature and research relevant to the topic was done in order to get information about the existing knowledge, identify gaps in the literature, and establish the theoretical framework for the thesis. Many papers and suggestions were received from my supervisors, which helped to improve this study. I contacted El-Watch AS for data on the matter, as well as my supervisors tried to connect with other companies to get data, but it was difficult to obtain it.

1.5 Structure of Main Report

Chapter 2: Offshore Wind farms Background

Chapter 3: Introduction to maintenance and maintenance strategies

Chapter 4: Maintenance in offshore wind farms

Chapter 5: Methodology

Chapter 6: Results

Chapter 7: Discussion

Chapter 8: Conclusion

The paper is structured as follows. In Chapter 2, background information on wind energy, its potential, its advantage, and the considerations that should be taken to achieve sustainability are introduced. In addition, the potential failure modes and their causes, the logistics required in offshore wind farms, as well as the Offshore Wind challenges are discussed. Chapter 3, presents background information on maintenance, its importance, and its strategies. Sustainability, digitalization, and the state of the art within digitalization of maintenance are reviewed and discussed. In Chapter 4, maintenance strategies in offshore wind farms are introduced and discussed, including their benefits, shortages, and challenges, and critical factors that affect maintenance costs are analyzed. Chapter 5 presents PLI estimation and criticality assessment as future tools for optimizing maintenance strategies in offshore wind farms. In Chapter 6, the role of Digital Technologies in Maintenance, and the Results from Using PLI estimation and criticality assessment are introduced. In Chapter 7, the results are discussed, and the research questions have been answered. Chapter 8 presents a conclusion and Recommendations for Further Work.

Chapter 2

Offshore wind farms background

2.1 Wind energy

Since wind power forms the backbone of sustainable energy systems, and has attractive characteristics such as availability and relatively low environmental footprint, the attention to offshore wind power notably increased in Europe, as well as wind farms gradually have flourished in size and power output as wind energy technology matures (Ren et al., 2021; Wu et al., 2019). Rystad Energy's analysis clarifies that installed offshore wind capacity is expected to increase from 10.5 GW in 2020 to 27.5 GW in 2026. Figure 1 shows the annual offshore wind power capacity in Europe by the end of 2022.

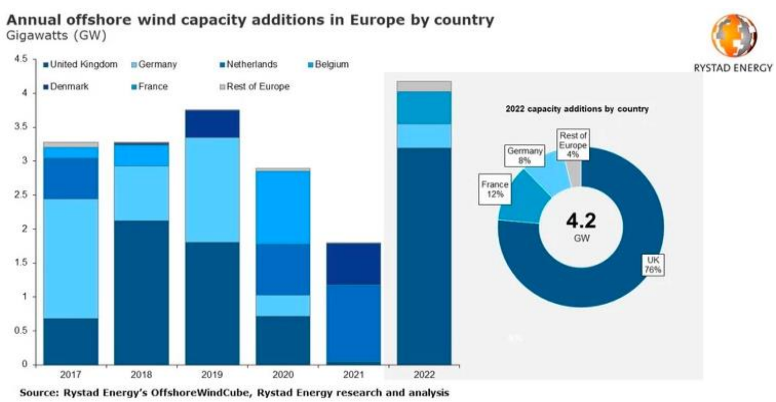

Figure 1 EU member state market shares for total installed capacity at the end of 2022 (renewablesnow, 2022)

Norway is one of many countries that has a growing need for new renewable energy sources to achieve its climate goals in terms of minimizing greenhouse gas emissions and moving away from fossil fuels (Government.no, 2023). Norway is already a considerable producer of renewable energy, primarily through hydropower and offshore wind potential (Government.no, 2023). Therefore, Norway's government has a target to implement supportive policies to enhance renewable energy development by allocating areas for 30,000 MW of offshore wind by 2040 (Government.no, 2023).

2.2 Wind energy and sustainability

Wind power is regarded as a renewable and sustainable energy source to meet the EU's climate and energy objectives for 2030, and reach the European Green Deal's targets in terms of sustainability (Rueter, 2021). Offshore wind farms are related closely to sustainability, as offshore wind farms contribute to facing climate change and reducing air pollution by generating clean energy with less greenhouse carbon emissions (Rueter, 2021). Furthermore, offshore wind farms are located far from the shore where there are large spaces for establishing and building the turbines and high capability to generate high amounts of power (Ren et al., 2021). Moreover, offshore wind farms are characterized by less noise impact and less visual pollution due to their location at the sea (Haghshenas et al., 2023; Ren et al., 2021). Generated power from wind can also be used to produce hydrogen and synthetic fuels in a climate-friendly way (Rueter, 2021). Even though wind power is considered to be an eco-friendly and sustainable source of energy (Rueter, 2021), there are certain considerations to keep in mind regarding its environmental impact. Here are some main points to understand:

- Offshore wind farms typically have high initial costs (Ren et al., 2021). The installation and manufacturing of wind turbines demand resources such as steel, concrete, and plastic with glass or carbon fiber (Ren et al., 2021; Rueter, 2021). These materials are used in the foundation, the tower, the gearbox, and the rotor blades, and require energy-intensive to manufacture (Ren et al., 2021; Rueter, 2021). In addition, waste inventory that occurs at every phase in the life cycle of offshore wind turbines causes environmental problems (wind turbines are generally operated for about 25 years), which demands efforts to improve the sustainability of wind turbine components, reconsider the topics linked to the recycling of waste resulting from maintenance, as well as find environmentally friendly materials to be used in turbines design (Ren et al., 2021; Rueter, 2021).

- The existence of turbines in harsh marine environments, and corrosive saltwater can cause risks to the durability and reliability of turbines (Ren et al., 2021). Implementing maintenance activities typically demands specific equipment and vessels which lead to increased air pollution and produce waste that is dangerous to wildlife (Ren et al., 2021). Therefore, it is preferable to choose the siting of wind power plants far from natural reserves in order to mitigate potential impacts, protect vulnerable species, and minimize the mortality rate resulting from collisions of birds with rotating blades (Ren et al., 2021; Rueter, 2021) . In addition, it is recommended to equip wind power plants with sensors, cameras, and software technologies to monitor noise levels, perform underwater surveys, and switch off the turbines when birds are very close (Rueter, 2021).
- Finally, wind capacity will be affected by climate change which leads to a slight decrease in productivity during summer months due to rising temperatures (Rueter, 2021).

2.3 Offshore Wind turbine components and common failures

Determining the types of failures and the causes leading to failures of the different components within the turbine is one of the important things that enable the identification of interactions between the turbines and their environment (Sahnoun et al., 2019). That could be contributed to making design changes, as well as implementing more effective maintenance (Sahnoun et al., 2019). Typical components in the turbine include the rotor blades, gearbox, generator, yaw system, pitch system, control system, sensors, electrical system, and foundation. In this section, a description of the functions and common failures of the critical components of offshore wind turbines including rotor blades, gearbox, generator, and electrical system will be provided. Figure 2 illustrates the components of wind turbine

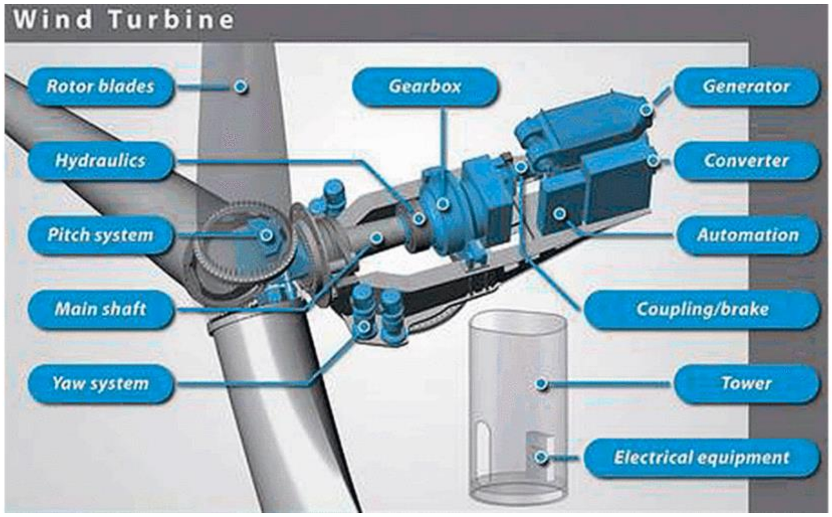

Figure 2 The components of wind turbine (Qiao & Lu, 2015)

Rotor blades

Rotor blades are one of the key parts of a wind turbine in terms of performance and cost of the wind power system (Qiao & Lu, 2015). Offshore wind turbines have three rotor blades that have a concave spherical shape to move toward the wind direction. The blades are designed with a shape that has a high lift-to-drag ratio that impacts effectively the performance when the wind blows, as well as avoids turbulence during rotation. The turbine blades are usually made from a lightweight stiff material that resists lightning strikes and prevents ice from forming (Jonker, 2017). Besides, they are equipped with a spar that provides stiffness and strength to withstand the wind load and blade weight. Major failures in the rotor blades are listed as follows (Jonker, 2017):

- Asymmetries occur either as the result of a mass imbalance or adjustment errors in the pitch angle.
- Fatigue is a result of aging, degradation, and long-term repetitive stresses. Fatigue is regarded as a reason that leads to decreased stiffness, cracks, increased surface roughness, and deformation of the blades.
- Corrosion is a result of long-term exposure to pollution, icing, and the existence of blowholes, or imbalanced loading of the blade. Moreover, Corrosion is the causative agent to the deformation of the blade, and it increases surface roughness and deterioration.

Gearboxes

Gearboxes in wind power transform mechanical power into electricity by increasing the rotational speed to the speed required by the generator to work (Jonker, 2017). For an economic and optimal design, it is important to have compact gear sets used in the gearbox that supply direct connection of the different shafts and provide various levels of the rotational speeds for wind turbine shafts (Abdul R. Beig, 2016; Jonker, 2017). Most gearbox failures are due to bearings failures where failures are usually caused by a lack of lubrication, used material defects, high loading, Bending fatigue, corrosion, axial cracking, and flaw in design and manufacture (Scheu et al., 2019). Lack of lubrication usually occurs due to using an improper lubricant type, water contamination and particulate contamination, and underfilling, which could lead to accelerated corrosion and component failure (Scheu et al., 2019) .

Generator

The generator is used to convert the mechanical energy in the rotating shaft to electrical energy by induction. Since the wind speed is variable in the wind turbine industry, it is preferable to use Double Fed Induction Generator (DFID), which is able to receive various frequencies and transform them to a steady 50/60 Hz (Abdul R. Beig, 2016; Jonker, 2017).The generator is the most important component in wind turbines, which is responsible for generating electricity and thus power production (Abdul R. Beig, 2016; Jonker, 2017). Therefore, it is necessary to keep the generator at work status to avoid losses of wind turbine shutdown and prevent the resulting costs from unplanned maintenance performance (Qiao & Lu, 2015). There are many reasons why the generator can fail, including manufacturing or design flaws, untrue composition, using unclean lubricant, insufficient electrical insulation, and electrical and mechanical failures (Jonker, 2017; Scheu et al., 2019). Electrical and mechanical failures are often caused by vibrations, imbalance, bearing failure, voltage irregularities, and cooling system failures that can result in excessive heat and generator combustion (Scheu et al., 2019).

Electrical system

The electrical system provides the connection between the power grid and the generator (Abdul R. Beig, 2016; Jonker, 2017). The design of the electrical system depends on the characteristics of the generators and the network joined to the project, as well as the regulations imposed upon it(Abdul R. Beig, 2016; Jonker, 2017). The electrical system controls the grid by maintaining both appropriate voltage and phase in order to get the demanded power (Abdul R. Beig, 2016; Jonker, 2017). The failure of the power electronic converter is the most common failure in this system. It happens usually due to temperature, vibration, and humidity (Scheu et al., 2019). Temperature is considered the main cause of the malfunctions. Additionally, leakage, short circuits, dielectric breakdown, migrating electric material, and separated leads are the results of Capacitor failure (Jonker, 2017; Scheu et al., 2019). In many cases, the internal and external cables could be degraded (Scheu et al., 2019). The degradation because of poor covering materials, fatigue, defect of vias, rustiness, or crack (Jonker, 2017; Scheu et al., 2019).

2.4 Classification of failure causes

According to (Sahnoun et al., 2019), the reasons for the failure of the different components within the turbine happen due to different factors such as the weather; human operating errors (human), and product quality or technical effects. These factors lead to various issues like fluid leakages from hydraulic components, breakages of blades/gearbox teeth, cracking of yaw drive shafts, corrosion, a breakdown in the motor unit, and vibration damage.

- Extreme weather conditions such as wind turbulence, lightning strikes, rainfall, frequent changes in temperature, and humidity affect different parts of the turbine, which leads to turbine degradation (Sahnoun et al., 2019).
- Human operating errors could occur due to frequent stopping and starting of the turbine, Improper installation bad design (Sahnoun et al., 2019).
- Technical effects affect the components of wind turbines and result in component degeneration. Technical effects include power surges, technical faults in electronic components, high vibration when the wind speed exceeds the required operating speed, particulate contamination in the gearbox, uncontrolled rotation and operation, and manufacturing faults (Sahnoun et al., 2019).

Figure 3 clarifies the failures and principal causes of failures. These causes affect directly the operation and maintenance costs, so they should be taken into account when improving a maintenance strategy (Sahnoun et al., 2019).

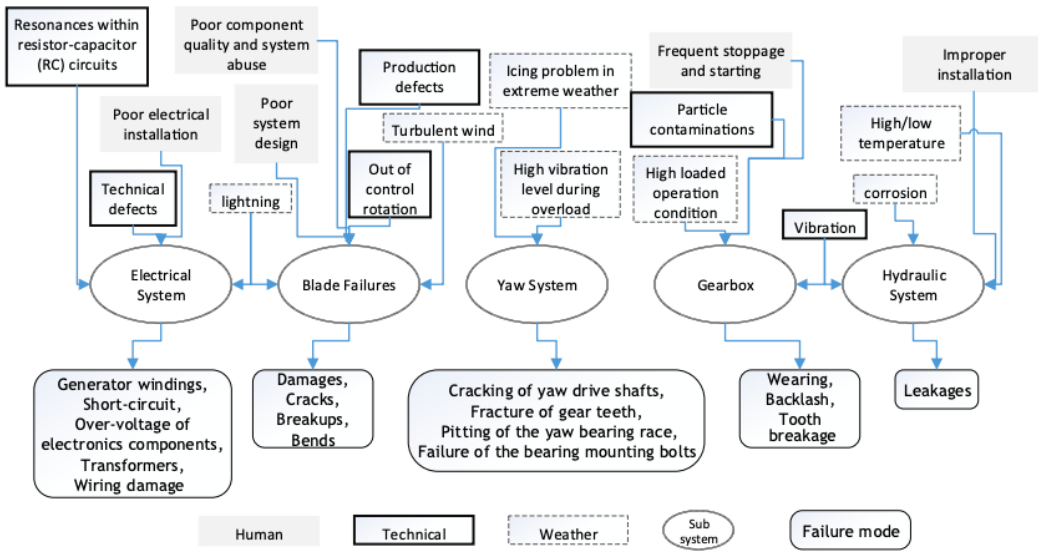

Figure 3 Principal causes of turbine failure (Sahnoun et al., 2019)

2.5 Availability of wind turbines

The availability of offshore wind turbines is regarded as a fundamental measure of reliability (Nilsson & Bertling, 2007). It is typically affected by harsh weather conditions and failures resulting from random environmental and mechanical loads that cause wear and damage (Besnard, 2013; Gonzalo et al., 2022). Therefore, it is possible to improve availability by improving maintenance planning and management to achieve and ensure the required level of energy production (Besnard, 2013; Gonzalo et al., 2022). According to (Gonzalo et al., 2022), the critical components in offshore wind farms including the gearbox, the electrical system, the blades, and the generator, contribute to high maintenance costs due to their frequent failure. Furthermore, these components require a lot of time or costly equipment to repair. Based on the Pareto chart, the failure of the gearbox is responsible for more than 80% of the risk factor and 40% of the cost of corrective maintenance, as well as leading to the longest downtime. Therefore, it should be monitored and inspected regularly (Besnard, 2013; Gonzalo et al., 2022). Figure 4 shows these variables in a Pareto chart to clarify the relative importance of the main components.

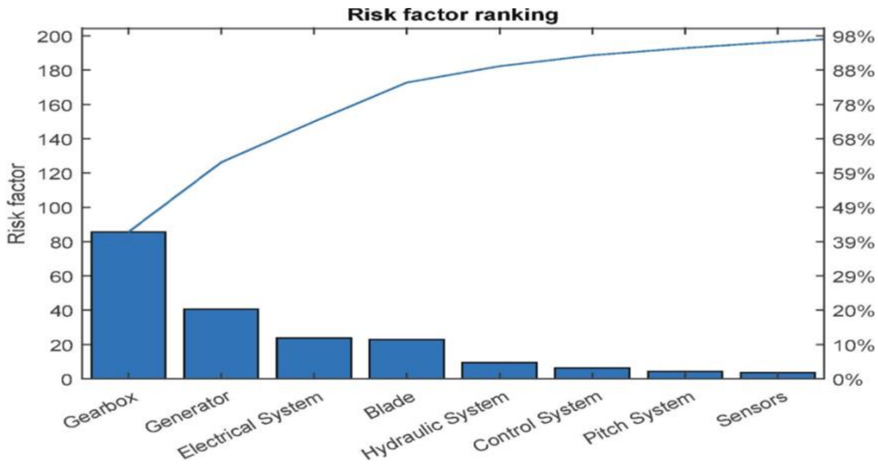

Figure 4 Pareto chart ranking component risk factors (Gonzalo et al., 2022)

2.6 Logistic

Logistics are an important factor in offshore wind energy which has a considerable effect on the profitability of wind projects, wind farm availability, and decrease O&M costs of offshore wind farms (Besnard, 2013; Shafiee, 2015) .Logistics represent all the resources required in order to perform maintenance activities. Logistics include maintenance labor, transportation means like workboats and helicopters, service vessels such as jack-up boats and crane ships, and spare parts (Besnard, 2013; Shafiee, 2015).

- **Personal staff**

Personnel staff generally includes overseen by a site and maintenance manager. The optimal number of personnel, working hours, and work-shift arrangement are defined based on the reliability of the wind turbine, the type of failure and maintenance activities that should be done, the availability of transportation, and the accessibility to the site according to weather conditions (Besnard, 2013).

- **Transportation**

The main tasks of the transportation systems are to transfer crews, technical, personnel, and large spare parts from shore to wind farms (Dalgic et al., 2015; Li et al., 2016). So, the number and type of crew transfer vessels should be compatible with the number of maintenance teams, the size of required equipment, and the needed tasks for implementing maintenance (Li et al., 2016). In this respect, there are various types of transport modes that are employed for different purposes, for example, specialized vessels for transfer for crews and technical personnel (CTVs), accommodation vessels, supply vessels for shipment of the required structural components along with supplying freight, multipurpose vessels that are equipped with the required equipment to offer maintenance functions, and floating cranes to carry out lifting operations in order to replace and maintain large-scale components, like the generators, gearboxes, and blades (Dalgic et al., 2015; Ren et al., 2021). In the case of maintenance, there are vessels for minor maintenance and vessels for major maintenance which are employed according to scheduled and unscheduled maintenance tasks in order to maintain turbines' operation and thus sustain power generation (Dalgic et al., 2015). The transportation systems are often equipped with ladders located on the foundation or gangway to access directly the wind turbines. In harsh weather conditions such as high wind speed and significant wave height, it could be unavailable to use CTVs due to safety constraints (Besnard, 2013). Therefore, to avoid the downtime of a wind farm and prevent massive losses of power generation, helicopters are utilized for the transportation of personnel and equipment in emergency situations for performing maintenance actions (Besnard, 2013; Dalgic et al., 2015; Li et al., 2016; Ren et al., 2021) . Figure *5* explains transportation solutions for offshore wind farms.

Figure 5 transportation solutions for offshore wind farms (Besnard, 2013)

- **Spare parts and tools**

To prevent a prolonged shutdown of offshore wind farms and reduce unwanted costs, it is necessary to optimize the availability of the spare parts needed for maintenance at the location which are used to change the failed components (Besnard, 2013; Shafiee, 2015). Therefore, it is important to define the critical spare parts that should be available, as well as choose the site of the main storage base, the maintenance workshop for repairing or replacing failed components, and supplier lead time contracts for each component. Furthermore, it is also required to check the availability of spare parts in the markets and the taken time to get them (Besnard, 2013).

2.7 Offshore Wind Challenges

Offshore wind farms are regarded as expensive compared with onshore installations (TWI, 2022). The maintenance and operation cost of offshore wind assets constitute a significant share of the LCOE of an offshore wind farm (Tjøm, 2022). Furthermore, the design, manufacture, and operate wind farms face a set of challenges that could affect their operational availability (TWI, 2022).

- In particular, building offshore wind farms in greater depths and further from shore where wind speed is high. Typically, that requires the use of larger-size turbines with robust and secure designs to be able to adapt to the harsh marine environment. This will be increased the cost of foundation design and manufacture. Furthermore, the installation of power cables under the sea floor requires long transmission lines to connect them to the electrical grid, which is extremely expensive and can lead to power losses during transmission(TWI, 2022).
- Extreme weather conditions particularly during heavy storms or hurricanes lead to increase wave action and high winds, which result in higher failure rates for the installed turbines due to degradation and corrosion (Tjøm, 2022). Moreover, the availability of microbial and biofouling in the seabed can cause fatigue and attrition as well as create challenges due to limited windows for carrying out inspection and maintenance requirements. This cause to high production losses, for example, a small amount of blade edge erosion leads to approximately a 5% drop in annual energy production (TWI, 2022).
- Offshore wind farms can have environmental impacts such as noise pollution, and the risk of marine animals and birds colliding with the rotating blades or tower. In addition, resulting waste during replacement operations and maintenance is dangerous to marine wildlife (Ren et al., 2021).
- Maintenance activities in offshore wind farms are considered costly due to many reasons (Tjøm, 2022):

- the difficult accessibility to an offshore wind farm in bad weather conditions raises downtime, thus decreasing power production (Ren et al., 2021).
- The need for specialized and expensive maintenance equipment such as a crane that is used in a lifting operation when there is a necessity for replacement or maintenance of a major component (Tjøm, 2022). Figure () shows an offshore lifting operation.
- The availability of transportation strategy for the technicians and spare parts to perform the maintenance when it is required. Sometimes, there are challenges related to transporting large-size components such as blades and towers to installation sites (Ren et al., 2021).

Chapter 3

Introduction to Maintenance and maintenance strategies

According to the NS-EN 13306, *Maintenance is defined as the combination of all technical and corresponding administrative actions intended to retain an item in, or restore it to, a state in which it can perform its required function*.

3.1 Importance of maintenance

In the past, maintenance was considered a necessary evil , but recently it become a procedure that creates value (Hersenius & Möller, 2011). Maintenance is regarded as a vital factor for companies. It contributes to retaining profitability over the long term by maintaining the capability of components or restoring them to a state in which they can perform the required function (Besnard, 2013; Hersenius & Möller, 2011).

Maintenance plays an effective role in asset management and is closely associated with production, safety, supply chain, and logistics (Okafor, 2022). The maintenance contributes to increasing the equipment’s uptime, efficiency, and performance (Okafor, 2022). Maintenance accounts for a great portion of the total operational costs (Ren et al., 2021). Maintenance costs include the cost of repairing or replacing the components, which represents the direct cost of maintenance, and the loss of production due to downtime associated with the lack of inspection or repairs of a faulty component (Ren et al., 2021). So performing maintenance before the failure happen could extend the lifetime of equipment, improve its reliability, reduce the resulting cost from the shutdown for repairs, as well as increase safety and availability (Duc et al., 2018) .

3.2 Maintenance strategies

According to NS-EN 13306 , the maintenance strategy is identified as the management method used in order to achieve the maintenance objectives. This policy assists to select the proper type of maintenance that should be implemented for each component and the right time to perform maintenance (Duc et al., 2018). Therefore, maintenance strategies may be classified into two main types, corrective and preventive maintenance. Preventive maintenance can be split into predetermined, condition-based, and predictive strategies, based on NS-EN 13306. Figure *6* illustrates the maintenance strategies.

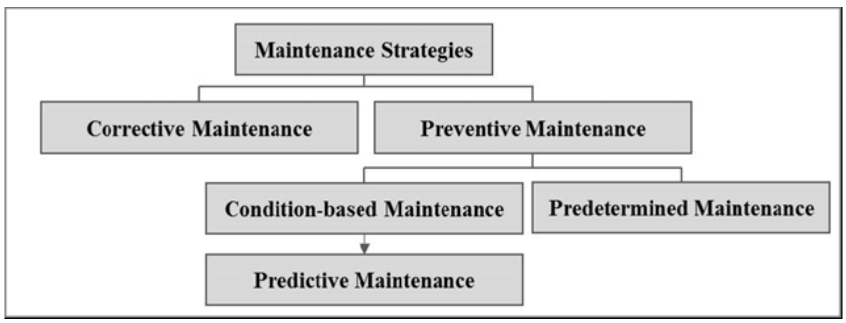

Figure 6 Overview of maintenance strategies (Duc et al., 2018)

Corrective maintenance

It is also known as “reactive maintenance” or "run-to-failure maintenance". This strategy is defined by IEEE (2000), as *The maintenance is carried out after a failure has occurred and is intended to restore an item to a state in which it can perform its required function*. It is considered the costliest maintenance policy, due to the longer unplanned downtimes and repair action delays, as well as the higher maintenance costs (Duc et al., 2018). It also requires the permanent availability of spare parts, crew, and transport in order to avoid production losses and reduce waiting time for repairing or replacing (Duc et al., 2018). However, it is still a convenient strategy for cheap components in the industry, and non-critical components that have only a limited effect on the performance or are redundant in the system (Meurs, 2017).

Preventive maintenance

According to NS-EN 13306, a preventive strategy usually refers to A preventive strategy usually refers to maintenance performed at predetermined intervals or according to prescribed criteria . This strategy is based on performing inspections and repairs on a set schedule during a system's normal operating conditions based on recommendations from the asset manufacturer, on the average life cycle of an asset, or analysis of historical data (Poór et al., 2019). Preventive maintenance programs are established using time or usage-based intervals for inspection, part replacement, and other pre-planned activities (Oztemel & Gursev, 2020). It aims to prevent unexpected costly breakdowns, as well as decrease the probability of an asset failing in the future, which improves uptime and prolongs the operating life of assets (Ren et al., 2021). Preventive maintenance strategies mainly involve predetermined, condition-based, and predictive strategies.

- **Time-based maintenance/ predetermined maintenance**

  Time -based maintenance is a type of preventive maintenance that is conducted according to determined time intervals (Besnard, 2013; Hersenius & Möller, 2011). It's considered appropriate for failures that are relative to the age of the components. In that case, the probability distribution of a failure can be established (Besnard, 2013; Hersenius & Möller, 2011). However, the actual condition of the assets is not taken into account. Additionally, it considers ineffective for assets that are used occasionally, which leads to waste RUL of items (Duc et al., 2018).

- **Condition-based maintenance**

  Condition-based maintenance is a strategy that monitors the health condition of an asset based on the measured data by a condition monitoring system (CMS) or inspections or fault analysis system to decide on the maintenance actions (Ren et al., 2021; Tjøm, 2022). The health condition describes the performance of the component or the degree of degradation. Thus the most effective repair methods are selected based on the component's real-time condition (Ren et al., 2021; Tjøm, 2022). This type of maintenance aims to prevent major failures, increase asset reliability, as well as reduce total maintenance costs by improving maintenance planning (Tjøm, 2022). However, the performance of a condition-based maintenance strategy could be affected by the number of false alarms resulting from a decrease in the reliability of the CMS. Thus, that will increase shutdown (Ren et al., 2021). The disadvantage of this strategy is the high investment cost of monitoring and prognostic equipment (Duc et al., 2018).

- **Predictive maintenance**

It emerged first time at the Hannover trade fair in 2011 in Germany. The NS-EN 13306 (CEN, 2010) defines predictive maintenance as "condition-based maintenance carried out following a forecast derived from repeated analysis or known characteristics and evaluation of the significant parameters of the degradation of the item." . It aims to monitor asset condition and performance by combining measurement data and parameter analysis to reveal anomalies in operation and possible defects in equipment, predict the remaining lifetime of a component (RUL), for then schedule maintenance before occurring of breakdown (Wang et al., 2016). The main idea behind using sensor technology in Predictive maintenance is conducting parametric analyses of sensor measurements in order to define the best time to implement maintenance events Therefore, maintenance frequency is as low as possible and reliability is as high as possible which contributes to decreasing downtime and cost of spare parts and supplies (Wang et al., 2016)The disadvantage of this strategy is high investment costs due to the absolute dependency on the sensor technology to make decisions (Wang et al., 2016).

Different maintenance strategies are illustrated in **Error! Reference source not found.** according to the degradation pattern and the scheduled maintenance interval.

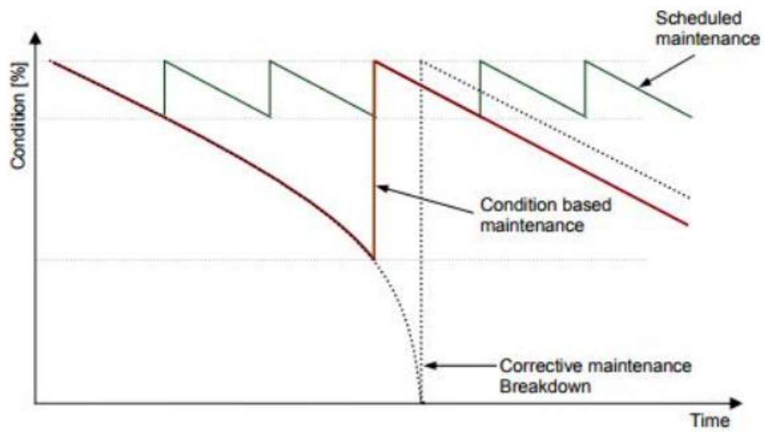

Figure 7 maintenance strategies; corrective, predictive, and condition-based maintenance (Jonker, 2017)

Opportunistic Maintenance

Opportunistic maintenance is a form of preventive maintenance, that combines preventive and corrective maintenance actions. It is also called opportunistic scheduling (OM). It can occur during the same visit to the location or during the same period (Tjøm, 2022). Where the maintenance team can inspect and maintain other components. The method can be very advantageous , where it can result in a 43% reduction in preventive maintenance costs by decreasing large setup costs and the number of visits to each location, thus reducing downtime (Ren et al., 2021; Tjøm, 2022).

3.3 The negative effects of maintenance

Even though maintenance contributes to increasing the reliability of components and the longevity of equipment (Karki & Porras, 2021). However, maintenance practices have impacts on the environment, economy, and society (Karki & Porras, 2021). Maintenance practices and actions cause direct environmentally problematic such as emissions, and the produced waste during maintenance like spare parts and oils (Ren et al., 2021). Maintenance operations execution demands the usage of transportation which leads to more energy usage, thus more emissions released (Ren et al., 2021). In addition, there are some materials like toxic lubricants and solvents that have a negative impact on the environment and humans in case of spilling (Karki & Porras, 2021). Furthermore, the noises generated by maintenance operations have negative impacts on the behavior of animals (Ren et al., 2021). Maintenance has a major influence on the economy due to high operation and maintenance costs including resources and logistics (Ren et al., 2021). Additionally, the delay in maintenance leads to revenue losses resulting from long downtimes and low availability because of failures and breakdowns (Karki & Porras, 2021). The maintenance impact on society appears through people's health and safety, where non-maintained assets and unexpected errors trigger serious health problems and accidents (Karki & Porras, 2021). Figure 8 illustrates the closed-loop product life cycle system. The raw materials and energy are taken from the environment in order to use them in manufacturing and maintenance. Then these materials would be recycled, redesigned, remanufactured, and reused. Finally, materials would be returned back to the environment in the form of waste and emissions (Karki & Porras, 2021) .

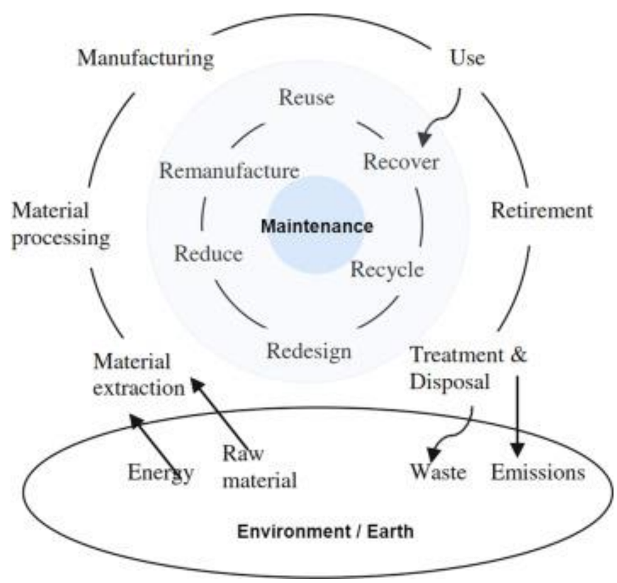

Figure 8 Closed loop product life cycle system (Al-Turki et al., 2014)

3.4 Sustainability

Sustainability refers to the taken actions aimed at the conservation of particular resources in order to meet the needs of the present without compromising the ability of future generations to meet their own needs (University). The sustainability aspect involves three performance measurement systems: economic, environmental, and social performance.

From a maintenance perspective, sustainability refers to executing maintenance activities in a way that minimizes negative impacts on the environment, preserves resources through increased reliability and availability, as well as supports long-term social and economic development (Karki & Porras, 2021).

The economic aspect includes proper asset management with the aim to carry on functioning and increase productivity and profitability over time (Karki & Porras, 2021). This includes monitoring the equipment continuously to ensure its health and condition and avoid breakdown, and repairing equipment instead of replacing it (Macchi et al., 2016). In contrast, that contributes to minimizing the maintenance and operation costs by lowing the need for maintenance, decreasing energy consumption, and reducing revenue losses resulting from the shutdown, non-quality, and low production rates (Karki & Porras, 2021; Macchi et al., 2016) . While environmental performance focuses on the impact of resource use, production waste, noise and hazardous emission, and social performance on ecological systems (Karki & Porras, 2021). The life cycle approach is considered necessary to determine the influence of decisions to develop products on the ecological systems (Karki & Porras, 2021). The following sides are taken into account during evaluate the life cycle approach: manufacturing a product, its processes, its component, its use, and its maintenance from the start of the life cycle to the end of life or disposal /recycling (Ren et al., 2021). This approach helps to identify practices and responsibilities that lower the impact on the environment such as waste and emission management, as well as the optimal usage of resources (Karki & Porras, 2021; Macchi et al., 2016). For social performance, the focus is on the impact of the work systems on employees' and workers' health and safety and community investment (Ren et al., 2021). In some work environments, workers are vulnerable to high risk, which could lead to injuries and deaths (Karki & Porras, 2021). Therefore, it is necessary to develop a quality, environment, health, and safety (QEHS) management system to manage the health and safety of operators (Karki & Porras, 2021).

3.5 Digitalization

Digitalization is one of the best approaches to optimizing the efficiency and effectiveness of maintenance. It refers to the use of digital technologies and advanced tools in maintenance processes such as advanced sensor devices, the Internet of Things (IoT), artificial intelligence (AI), machine learning, predictive analytics, etc (Karki & Porras, 2021). Sensor devices allow the remote monitoring of equipment performance continuously, where the collected data on performance is shown as a graph that identifies and visualizes the structural performance under various operational conditions. The behavior of equipment is analyzed by employing IoT, AI, ML, Cyber-physical Systems, and other intelligent technologies to detect any anomalies and predict when equipment is likely to fail. This allows for planning maintenance activities proactively based on the actual condition of the equipment, reducing downtime and costs associated with maintenance operations. Furthermore, Digitalization contributes to optimizing asset management and improving its operating performances; particularly for remote or difficult-to-access equipment; based on historical faults, troubleshooting, predictions analysis, and convenient decision-making of a physical system. In addition, digital technologies such as drones, sensors, and cameras can also decrease the need for personnel to work at heights, in hazardous environments, or in case of harsh weather conditions, which assists to improve safety for maintenance teams, as well as reduce costs and environmental impacts associated with maintenance activities, thus enhance sustainability.

Digital technologies

- Artificial intelligence (AI) refers to the ability of a computer system to learn automatically from patterns in the combined data in an IoT hub by using intelligent algorithms and adapting to new inputs for carrying out tasks that normally demand human intelligence in order to reveal anomalies and degradation, thus proper decision-making for maintenance (Deepa et al., 2022).
- Machine learning (ML) is a subset of artificial intelligence that includes developing algorithms and models able to learn from data and make future predictions or decisions without being explicitly programmed to do so (Deepa et al., 2022) .
- Sensors can be used to monitor the current state of equipment and reveal minor problems before they become major (El-watch, 2023). Sensors gather data from physical environments and transform their physical properties like speed, temperature, and pressure into electrical signals that can be analyzed by a computer to detect changes (El-watch, 2023). This advanced equipment allows operators to make preventative and cost-efficient decisions, as well as predict the right time for maintenance execution. Here are some of the current state-of-the-art technologies for condition monitoring :

- Oil analysis: Oil analysis is utilized to analyze lubricant and assess its quality by knowing the nature, amount, and size of the particles that are considered as an indication for the healthiness of the components, and help to define the potential issues (Tchakoua et al., 2014).
- Vibration monitoring: This technology uses sensors to measure the vibrations of machine components, allowing to detection of anomalies and mechanical failures in an early stage (Jonker, 2017). Hence, identifying probable problems before they lead to failure and the severity of the fault based on the frequencies of the vibrations (Tchakoua et al., 2014).
- Acoustic monitoring: Through the collected information from sensors, the sounds produced by machine components are analyzed to detect if there are any deviations from normal sounds, thus diagnosing possible issues resulting from mechanical overloading (Jonker, 2017; Tchakoua et al., 2014).
- Ultrasound monitoring: This technology uses high-frequency sound waves to assess cracks and detect defects in machine components (Jonker, 2017). In case of the existence of anomalies like cracks, the wave will reflect backward, which allows for avoiding major problems (Jonker, 2017).
- Strain monitoring: the technique determines stress and deflection, as well as measures microscopic length changes in a structure that occurs under the effect of external forces on an object (Jonker, 2017; Tchakoua et al., 2014) .
- Thermography : it is an approach utilized to reveal material failures according to subsurface temperature gradients (Jonker, 2017).
- Visual inspection : it is used to assess the health condition of components in the system based on human sensory information (Jonker, 2017; Tchakoua et al., 2014).
- Electrical effects : the technique is used to evaluate the situation of electrical components (input/output) by voltage and current analysis to reveal isolation faults.
- Temperature: it is one of the used simple measurements. However, temperature information should be combined with other techniques (Jonker, 2017; Tchakoua et al., 2014). The deviation of temperatures from the usual temperature could be an

indication of excessive stress and friction or faulty electrical connections (Jonker, 2017; Tchakoua et al., 2014)

  - Optical fiber monitoring : it is a way to monitor the structural health of components by detecting variations in temperature, strain, and vibration (HBMCompany, 2022).
  - Torsional vibration: it is a used way to reveal any abrupt changes that occur due to loads (HBMCompany, 2022)
  - Radiographic inspection: is a technique that uses X-ray to examine the internal structure of a material, and reveal anomalies such as cracks and voids by analyzing the resulting image from passing radiation through the material (Tchakoua et al., 2014).
  - Generator power output: in this way, sensors are used to measure the amount of generated electricity. in the case of a reduction of produced electrical power from the usual amount of generated power, sensors will detect this change (HBMCompany, 2022).

- Digital twins: The use of digital twins is allowing to establish virtual replicas of processes, and components by using data from IoT sensors, and devices connected to the internet to provide a near real-time connection between both the physical and virtual worlds (Haghshenas et al., 2023). A digital twin enables the industry to reveal faults and anomalies, anticipate findings more accurately, and optimize workflows (Xia & Zou, 2023).
- Drones can contribute effectively to maintenance tasks, where they can take part in the inspection and monitoring of equipment and structures particularly in areas where it may be difficult to access due to bad weather conditions or height (Ren et al., 2021). Furthermore, drones can be used to clean hard-to-reach areas. Therefore, drones assist to minimize costs and enhance worker safety.

Chapter 4

Offshore wind turbine operations and maintenance

Maintenance is a critical factor that ensures the safe and reliable operation of offshore wind farms (Ren et al., 2021). Effective maintenance strategies assist to decrease downtime resulting from aging equipment, thus extending the life of equipment, minimizing maintenance costs, and reducing the number of emergency repairs (Dalgic et al., 2015; Ren et al., 2021). The choice of maintenance strategy depends on many factors including the criticality of equipment, the availability of resources demanded to perform maintenance activities, the support organization's goals, and the cost (Besnard, 2013). Due to the harsh marine environment, offshore wind farms could be exposed frequently to failure, which demands visiting wind farms periodically to avoid a long shutdown (Ren et al., 2021). Hence, it is important to exist an adequate number of transportation means to transport the heavy spare parts and maintenance teams for repair and maintenance tasks, as well as transfer faulty components to maintenance accommodations in the port (Dalgic et al., 2015; Shafiee, 2015). That could lead to expensive costs. False alarms can sometimes lead to unnecessary inefficient visits, on the one hand, increasing unwanted costs (Ren et al., 2021). The unavailability of transportation means or technicians also causes a maintenance backlog which leads to long downtimes and expensive rental costs for transportation means (Dalgic et al., 2015; Shafiee, 2015).

4.1 Maintenance strategies

There are several maintenance strategies that are commonly used for offshore wind farms. The choice of maintenance strategy relay on many factors such as the criticality of components and equipment, the environmental conditions, accessibility, and cost (Ren et al., 2021). Maintenance strategies are typically classified as corrective maintenance, preventive maintenance, and opportunistic maintenance based on when maintenance is performed (Ren et al., 2021)

- **Corrective maintenance**

Corrective maintenance is a failure-based maintenance strategy in which maintenance is performed only when equipment breaks down (Ren et al., 2021). The corrective maintenance strategy is typically impractical in wind farms due to the bad weather conditions which typically lower the system reliability and increase the equipment failure rate, which demands high repair costs (Ren et al., 2021). Furthermore, it is so costly due to the need for the availability of components, transport, and personnel when failure is noticed (Meurs, 2017; Ren et al., 2021). Moreover, it considers unwanted, where in some cases it is performed after a long downtime which leads to a loss of production (Besnard, 2013; Ren et al., 2021). The corrective maintenance strategy could be efficient in the case of non-critical components that have only a limited effect on performance , revenue costs, or negative externality such as the possible pollution of seawater due to a component failure (Meurs, 2017).

- **Preventive strategy**

Preventive maintenance can be defined as maintaining the equipment to hinder potential malfunctioning (Karyotakis & Bucknall, 2010). Maintenance activities can be usually executed at a given period of time where there are fixed intervals between each repair and maintenance period, or at predetermined levels of power generation (Meurs, 2017; Ren et al., 2021). The number of planned intervention intervals in a year is determined according to the reliability of each component, and the accessibility to the site based on weather conditions. This means that planned repair maintenance will happen at the same times every year so allowing to eliminate the unplanned repair events (Meurs, 2017). Furthermore, this strategy permits optimal utilization of maintenance equipment through scheduling maintenance visits at convenient weather status, and therefore evades cancellations or delaying expeditions, which contributes to decreasing unwanted maintenance costs (Karyotakis & Bucknall, 2010; Meurs, 2017). Additionally, through inspections and maintenance operations that are executed during each visit, it will be determined the spare parts will be needed and be purchased in time practice, which reduces the unexpected and surprising maintenance costs of the offshore wind farm (Meurs, 2017). As well, a planned intervention maintenance strategy enables to performance of maintenance and repair activities for many offshore wind turbines in one maintenance expedition, which reduces the maintenance resource costs (Karyotakis & Bucknall, 2010) . On the other hand, If a failure occurs between two intervention intervals, the wind turbine will be on downtime until the next planned visit to perform repairs, which will result in a loss of revenue (Karyotakis & Bucknall, 2010). Preventive maintenance could be an effective strategy by optimizing the choice of maintenance interval (Ren et al., 2021).

- **Condition-based maintenance (CBM)**

Condition-based maintenance is a preventive maintenance strategy that monitors the performance and health of the system and measures the condition parameters of each component in real time by using a condition Monitoring System (CMS) (Ren et al., 2021; Zhang et al., 2015). Sensors are installed into wind turbines to collect data, and then process it to identify system health conditions, and potential issues before they occur, thus decision-making on maintenance scheduling and service action (Zhang et al., 2015). This strategy is commonly used for offshore wind farms, for instance, vibration measurement, acoustic emission, ultrasonic, and thermography techniques are implemented for essential components in wind turbines with the aim to detect degradation or a change in the condition of a component, subsequently, avoid major failures that lead to an unexpected shutdown (Ren et al., 2021). The purpose of condition monitoring is to ensure the constant operation of wind turbines with continuous monitoring and analysis, thereby ensuring optimal use of the remaining useful life of the turbines, improving maintenance planning, reducing frequent visits to the sites, and thus minimizing maintenance expenses (Zhang et al., 2015). The disadvantage of this strategy is monitoring devices that require extra costs (Zhang et al., 2015). Additionally, sometimes true negatives (no alarm) or false alerts could happen, which is possible to affect negatively the availability of offshore wind farms and increase maintenance costs because of unnecessary visits (Ren et al., 2021). Figure() illustrates the types of condition-monitoring techniques and analytics methods used to monitor and inspect the components in an offshore wind turbine.

	Nacele	Tower	Blade	Bearings	Shaft	Gearbox	Generator
Vibration analysis	✓		✓	✓	✓	✓	✓
Torsional vibration					✓	✓	
Acoustics Emission		✓	✓	✓	✓	✓	
Oil analysis				✓		✓	✓
Strain measurement		✓	✓				
Optical fiber monitoring			✓				
Electrical effects				✓			✓
Temperature	✓			✓		✓	✓
Ultrasonic testing techniques		✓	✓				
Thermography	✓		✓	✓	✓	✓	✓
Visual inspection	✓		✓	✓		✓	✓
Radiographic inspection.		✓	✓				
Generator power output							✓

Figure 9 The monitoring and analysis methods to different components (Ren et al., 2021)

Figure 9 shows different used methods that help to examine the health of components, as well as reveal any changes in the conditions (Besnard, 2013). Ultrasonic or thermography inspection is utilized to inspect blades, generator, gearbox, and shaft (Besnard, 2013). Furthermore, it used also strain measurements or optical fiber monitoring, or radiographic inspection that can detect damages resulting from delamination or cracks in blades (Besnard, 2013; Jonker, 2017) . Usually, thermography inspection is a method for detecting anomalies in electrical components such as generators (Besnard, 2013; Jonker, 2017). Vibration and oil analysis of the generator, gearbox, and bearings of a wind turbine are a common operations for offshore wind turbines that supply information on the deterioration state of several components of the offshore wind turbines (Jonker, 2017).

- **Time-based maintenance**

Time-based maintenance is a type of preventive maintenance, which is conducted in accordance with a predetermined schedule based on the known failure pattern of the components regardless of the current condition of the equipment (Zhang et al., 2015). Components of the offshore wind turbine are usually exposed to wear and tear, so it is possible to predict the events of failure over time, and therefore maintenance tasks can be scheduled accordingly (Zhang et al., 2015). Time-based maintenance can be a beneficial strategy for ensuring the reliability and safety of offshore wind turbines, but it may also lead to loss of production time, as well as unnecessary maintenance costs if components do not require servicing at the scheduled time (Zhang et al., 2015).

- **Predictive maintenance**

Predictive maintenance is an advanced type of condition-based maintenance that utilizes advanced analytics and machine learning algorithms to predict when equipment maintenance is required before fault occurrence, as well as forecast the remaining useful life of components (Ren et al., 2021; Tjøm, 2022). Though the used equipment is expensive, this approach can assist to optimize maintenance schedules by reducing maintenance frequency and time, and logistics costs (Ren et al., 2021). Moreover, it contributes to minimizing the risk of equipment failure and OWF downtime (Ren et al., 2021).

- **Opportunistic maintenance**

Opportunistic maintenance is an unscheduled maintenance approach that is performed during the same visit or time period to carry out scheduled maintenance (Ren et al., 2021; Tjøm, 2022). Opportunistic maintenance in offshore wind farms includes conducting maintenance tasks based on observed changes in the status of the wind turbines or their components such as the performance, vibration, and temperature (Ren et al., 2021). It involves replacing or maintaining components preventively to stay in a good state (Ren et al., 2021). This could help to save costs and increase the availability of offshore wind turbines (Ren et al., 2021; Tjøm, 2022). However, the performance of opportunistic maintenance relies on the reliability and accuracy of the monitoring systems used to reveal abnormal deviations in the wind turbines, as well as the availability of maintenance crews and spare parts to solve issues as they arise (Ren et al., 2021).
The Table 1 comparison of different maintenance types used for offshore wind farms shows a comparison of different maintenance types used for offshore wind farms.

	Corrective maintenance	Time-based maintenance	Condition-based maintenance	Predictive maintenance
Trigger	When failure occurs	predetermined schedule	Real-time measurement	Real-time measurement and data analytics
Initial cost	low	Medium, due to regular maintenance activities	High due to monitoring devices that require extra costs	Too high due to costly used advanced equipment
Number of failures	High	Low to medium	Low	Lower than Condition-based maintenance
Unnecessary visits	low	Medium , where Maintenance activities are usually executed at a given period of time	Low, sometimes the false alerts lead to unnecessary visits.	Low
Unplanned maintenance	High	low	Medium according to the health of system	Medium
Maintenance regarding failures	After	Before or after	shortly after detecting degradation or a change in the condition of a component	Before
Downtime	High	Medium	Low to medium	low
Level of automation	Low	Low to medium	Medium to high	High
Operator safety	High, unexpected failures and emergency repair activities, which could be under adverse weather	Medium, maintenance activities are planned and conducted under controlled conditions	Low, Operators can perform tasks under controlled conditions	Low, Operators can perform tasks under controlled conditions
Ecological protection	High where it does not proactively address issues that could lead to environmental damage	Medium, due to the frequent visits to perform maitenance	Low, due to minimizing unnecessary maintenance activities	Low, due to due to minimizing the likelihood of unexpected component failures that could harm the environment, as well as reducing Unnecessary visits

Table 1 comparison of different maintenance types used for offshore wind farms

4.2 Typical Challenges for maintenance in offshore wind turbines

Maintenance activities are considered significant for offshore wind farms that help to raise the reliability of assets in OWF and lower unwanted costs. The maintenance challenges that face Offshore wind farms are due to many reasons (Sahnoun et al., 2019):

- Site conditions: the distance from coastal facilities to maintenance accommodations, the number of wind turbines that are located by each maintenance accommodation, the distance between the wind turbines, water depth, and wind direction affect the accessibility to locations to perform maintenance actions when needed, particularly during harsh weather conditions (Catapult, 2022; Shafiee, 2015). Moreover, the logistics costs will be higher (Shafiee, 2015). So the choice of site and reliable design of offshore wind farms is so important to avoid costly logistics and decrease production losses (Shafiee, 2015).
- Turbine size: large turbines generally need more tricky and specialized maintenance procedures. For instance, larger turbines may demand larger cranes and specialized equipment for repairs, which can increase the cost of maintenance and the time required to inspect and repair. Furthermore, the larger turbines can expose higher stresses, which can lead to more frequent maintenance needs (Sahnoun et al., 2019).
- Adverse weather conditions like high winds, waves, and salt spray can cause corrosion, degradation, and wear, which can impact the performance and lifespan of the component (Catapult, 2022). Additionally, a bad marine environment is regarded as a restriction factor for maintenance activities, where it reduces access to turbines, which delays maintenance activities, increases downtime for equipment, and decreases energy production (Besnard, 2013; Tjøm, 2022). Wind constraints are exemplified in the Table *2*

Wind speed [m/s]	Restrictions
≥30	*No access site*
≥20	*No climbing turbines*
≥18	*No opening of the roof doors*
≥15	*No working on the roof of the nacelle*
≥12	*No work in the hub*
≥10	*No lifting roof of nacelle*
≥7	*No blade removal*
≥5	*No climbing on the met masts*

Table 2 Example of wind constraints for maintenance activities (Hersenius & Möller, 2011)

- High cost of maintenance: Maintenance in offshore wind farms is expensive due to the high cost of specialized equipment, transportation means, and personnel staff required to carry out maintenance tasks (Besnard, 2013). In general, a certain number of transportation systems such as jack-up boats and crane ships are used to transport weight spare parts like blades, generators, gearboxes, or towers from the port to on-site warehouses, where it is hard to store spare parts and equipment on-site due to the limited space there (Besnard, 2013; Shafiee, 2015; Tjøm, 2022). Likewise, a helicopter is used in the case of a harsh offshore environment when wind speeds of about 20 m/s, and when the accessibility of the locations by vessels is limited due to the heavy wind speed and high waves (Besnard, 2013; Hersenius & Möller, 2011). Helicopters are usually less affected by bad weather conditions and can quickly transport both required equipment and personnel staff. Furthermore, a helicopter requires qualified human resources and good visibility to reach a wind farm, as well as helipads to be able to land on a site (Hersenius & Möller, 2011). Therefore, it considers very costly. Additionally, workboats are also utilized to transfer the crew and technical personnel, and also load the failed turbine items to maintenance accommodations (Shafiee, 2015). Therefore, maintenance activities become more cost-effective, when a sufficient number of transportation means as well as maintenance teams for repair actions are allocated. That helps to keep the turbines operational and avoid expensive hiring charges for supply vessels (Besnard, 2013; Shafiee, 2015; Tjøm, 2022).

- Data management: Offshore wind farms are equipped with sensors that collect large amounts of data, including operational data, maintenance data, and environmental data. Managing and analyzing this data can be critical and impact maintenance decision-making (Ren et al., 2021). Managing and analyzing data efficiently requires accurate and reliable data, the availability of skilled personnel to analyze data effectively, as well as the implementation of robust cybersecurity measures to prevent data breaches (Ren et al., 2021).
- Environmental consideration: Even though offshore wind farms contribute highly to decreasing the use of fossil fuels, many environmental impacts, such as noise pollution resulting from installing the foundations to the seabed and the movement of the blades can harm marine ecosystems and kill animals like birds (Ren et al., 2021). In addition, disposition of the large components like blades and towers creates waste and potentially releases harmful chemicals (Ren et al., 2021). Furthermore, some components contain lubricants and chemicals that can be harmful if they are released into the environment. Moreover, the use of vessels to transfer staff and spare parts to the site leads to increasing GHG (Greenhouse gas) emissions that affect the environment negatively (Ren et al., 2021).

4.3 Maintenance activities at offshore wind power systems

Maintenance activities at offshore wind farm systems are made up typically of CM activities and PM involving scheduled service maintenance actions (Hersenius & Möller, 2011). The information about maintenance activities and duration of repairs usually are provided according to the failure frequencies of components (Hersenius & Möller, 2011). Typically, components are classified based on failure frequencies to (Hersenius & Möller, 2011) :

- Heavy components: these components require severe repairs and specific means like a crane to perform maintenance actions.
- Large components such as tower, blades, and so on.
- Small parts, which include the least critical faults, and need 24 hours or less to repair.

Offshore wind turbines are often maintained only once a year during the spring or summer season due to the hard accessibility during bad marine conditions, as well as high logistic cost (Besnard, 2013). Yearly maintenance actions take generally 2-3 days per wind turbine and include (Besnard, 2013):

- *Changes of lubrication systems and oil filters*
- *Check of blades and slip ring*
- *Inspection with respect to leakage*
- *Test of safety systems and pad brake*
- *Strength testing and retightening bolts*
- *Oil sampling & analysis for the gearbox*
- *Visual inspection of the blades.*

4.4 The availability of offshore wind farm

The availability of offshore wind farms indicates the percentage of time that the turbines are able to generate electricity, as compared to the total time that they are predicted to be operating (Hersenius & Möller, 2011; Jonker, 2017). The availability of offshore wind farms is essential for ensuring that the wind farm is producing the maximum amount of energy possible, and for obtaining a high return on investment (Besnard, 2013). The availability of offshore wind farms is impacted typically by the following factors:

- Regular maintenance and repair time: Executing maintenance activities regularly are essential for ensuring turbine performance (Hersenius & Möller, 2011). However, this demands downtime, which can impact the availability of offshore wind farms and the generation of electricity. Furthermore, the false alarms that are given by advanced control systems lead to unnecessary visits to carry out maintenance actions, and thus wind turbines will be out of service (Hersenius & Möller, 2011; Ren et al., 2021).
- Weather conditions: Offshore wind farms are exposed to a range of weather conditions, including wind speed, storms, and significant wave height. These conditions lead to higher stress and load, which will increase failure frequencies and decrease reliability, subsequently impacting the availability of the turbines (Hersenius & Möller, 2011; Ren et al., 2021). As well, Weather conditions can restrict the accessibility to the location to

perform maintenance, wind turbines may need to be shut down for safety reasons (Besnard, 2013).

- Equipment failures: wind turbines can be subject to equipment failures due to bad quality and components with lower reliability, that demand frequent repairs or replacement. These failures can impact negatively the availability of the turbines (Hersenius & Möller, 2011). For example, The replacement of the main components like the gearbox is responsible for the longest downtime per failure, and replacement cost forms 80% of the cost of corrective maintenance in Figure 4. *The downtime results from the long lead time for the spare parts and crane ship* (Besnard, 2013).
- Grid connection issues: Offshore wind farms must be linked to the electrical grid in order to distribute the produced electricity. Issues with the grid connection can impact the availability of the turbines, where the reliability of the internal electrical grid and the transmission electrical system is considered a very important factor for the availability (Besnard, 2013).

4.5 Cost analysis

LCOE (Levelized cost of energy) is defined the lifetime average cost for the energy produced from a specific power source per megawatt-hour, quoted in today's prices (Catapult, 2022; Ren et al., 2021). LCOE gathers costs and energy production into one metric, therefore it is usually used to evaluate and compare the cost of electricity production from different power sources and at different sites (Catapult, 2022; Ren et al., 2021).

The total cost consists of the capital expenditure (CapEx) that includes development expenditure, cost related to wind turbine components, and the cost of associated power production components, as well as the operational expenditure (OpEx) that can be divided into operating and maintenance costs, and the decommissioning expenditure (DecEx) (Catapult, 2022; Ren et al., 2021). Figure 10 demonstrates cost breakdown of offshore wind turbine.

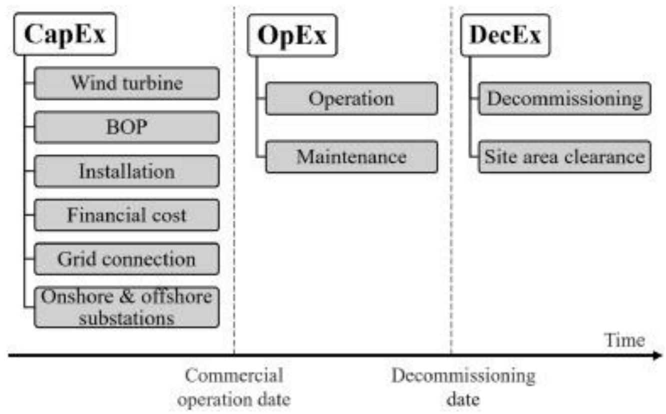

Figure 10 Cost breakdown of offshore wind turbine (Ren et al., 2021)

Operational expenditure (OPEX) that involves Operation and Maintenance (O&M) costs is considered a main contributor to the LCOE (Levelized cost of energy), which accounts for around 25-30% of their total investment cost (Catapult, 2022; Ren et al., 2021). Hence, minimizing O&M costs is an efficient way to control the LCOE, as well as reduce the downtime caused by aging equipment (Shafiee, 2015). Figure 11 shows the contribution of each major cost element to levelized cost of energy (LCOE).

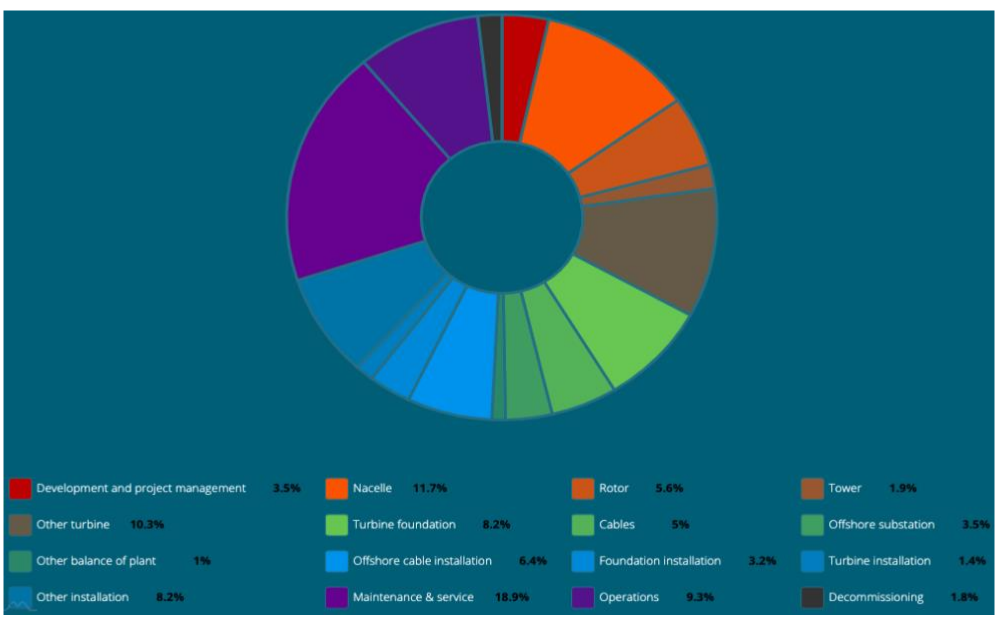

Figure 11 contribution of each major cost element to levelized cost of energy (Catapult, 2022)

In general, the maintenance costs of offshore wind farms are regarded as high due to the changing conditions of the weather, where the crew cannot safely work and carry out maintenance operations when waves exceed 1.5m or wind speeds are greater than 12 m/s (Jonker, 2017). Thus, the waiting time for a weather window is the worst and longest in winter (Jonker, 2017). Maintenance costs are made up of the following costs (Dalgic et al., 2015):

• Direct costs: equipment costs which are the highest, spare part costs, and transportation costs (vessels and associated costs).

• Fixed costs (port, insurance, bidding, etc.), crew, and technician costs.

• Indirect costs: lost production costs caused by a lack of maintenance.

Therefore, maintenance plays an important role in increasing the reliability and availability over the lifetime of an offshore wind farm and thus takes a part considerably in the LCOE (Dalgic et al., 2015; Shafiee, 2015) .

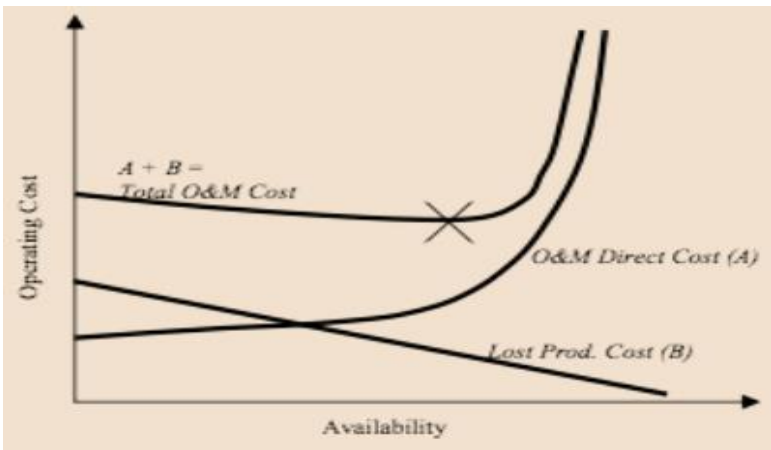

Figure 12 : Indicative plot of wind farm O&M optimization(Hersenius & Möller, 2011)

Figure 12 illustrates that high availability can be obtained with high costs of O&M, where maintenance plays an important role in increasing the reliability and availability over the lifetime of an offshore wind farm, and thus takes a part considerably in the LCOE (Dalgic et al., 2015). The “x” refers to the optimal point on the total O&M cost curve, where the highest availability to the lowest possible operating cost. Therefore, it could be beneficial to schedule and perform maintenance when the revenue losses are minimal (Hersenius & Möller, 2011). Where in the summer season the revenue losses are about one-third of the revenue losses in the winter season when peak production happens (Hersenius & Möller, 2011). Maintenance actions usually include orderly inspections and repairs to correct any failures and damages or substitute faulty components (Dalgic et al., 2015).

4.6 Maintenance optimization

Maintenance optimization is an approach aimed at improving assets' reliability, rising efficiency, increasing safety and ecological protection, and minimizing costs by identifying improvements that should be implemented in the maintenance process by achieving the optimal balance between the costs and the benefits of maintenance (Besnard, 2013; J.A. Andrawus, 2008). Maintenance optimization is achieved by choosing the appropriate maintenance for each component in the system based on their failure modes, probabilities, and consequences, as well as improving the resources demanded to carry out the maintenance activities e.g. the size of the maintenance staff, qualified workforce, the availability of transportation strategy, spare parts, the buy/hire of maintenance equipment (Besnard, 2013; J.A. Andrawus, 2008). Furthermore, the time of implementing maintenance and inspection it should be taken into consideration when the maintenance process is optimized (Besnard, 2013; J.A. Andrawus, 2008).

Chapter 5

Methodology

High O&M costs, safety risks, environmental impact, and financial losses are regarded as the main challenges which restrict the development of offshore wind energy (Ren et al., 2021). The method of performance measurement used in this thesis came from the theories of O&M strategy based on condition monitoring and advanced analytics, and the use of digital technologies that contribute to enhancing performance and improving decision-making (Karki & Porras, 2021). These technologies provide the capability to monitor the current state of the system and its critical components, as well as collect data from various sources. Advanced analytics techniques like machine learning and artificial intelligence analyze collected data in order to recognize patterns and anomalies, and thus predict failure and determine the right time to perform maintenance (Karki & Porras, 2021; Xia & Zou, 2023) . This approach enables optimized decisions regarding maintenance, asset management, workers' safety, and marine ecology safety. The effect of digital techniques on offshore wind farms on the maintenance and production function can be clarified by the criticality assessment. Given the role of criticality assessment and PLI cube in the development of other sectors, it is proposed to use them in offshore wind farms in order to develop and sustain the renewable energy sector. The criticality assessment is an essential element to improve maintenance planning by prioritizing maintenance activities and allocating resources effectively (Rødseth et al., 2020). It assists to identify assets that are crucial for the operation, safety, and performance of the system. It also provides an evaluation of both the probability and consequences of each failure of the equipment while taking into consideration several factors such as safety risks, production interruptions, environmental impact, and financial losses (Rødseth et al., 2020). The PLI (Profit Loss Indicator) cube provides an analysis of the financial performance of the wind farm. The analysis gives insights into the profitability, revenue, returns, and lost income. Therefore, in this thesis, it is suggested to measure the effect of digital techniques on offshore wind farms on the maintenance and production function by the criticality assessment. Due to the limited literature about the maintenance of offshore wind turbines, terminologies from the background and theories which were derived from literature reviews from another field were used to explain the findings resulting from the use of criticality assessment and PLI Cube in offshore wind farms.

5.1 Literature review method

A literature search was done to formulate a problem statement. It was found that there is still a significant gap in clarifying the impact of digitalization on maintenance in offshore wind farms from a sustainability perspective. Literature was sourced from different databases for scientific literature, such as Oria, Science Direct, Scopus, Google Scholar, and NTNU's Library. In the selection of research keywords, the main keywords "offshore wind farm", "maintenance", "sustainability" and "digitalization" were used firstly. Earlier literature texts were carefully reviewed to select the texts which are relevant to the topic, and remove those not related to the field of "optimization". Furthermore, my supervisors tried to improve my work by sending some papers related to maintenance in offshore wind farms, sustainability in offshore wind farms, and maintenance strategies. These papers were very valuable and inspiring. The literature " Smart Maintenance in Asset Management –application with Deep Learning" was the inspiration to use the criticality assessment and PLI as tools to optimize maintenance in offshore wind farms in order to achieve sustainability. Especially since the company "Oceaneering" I am cooperating with in writing my master's thesis is interested in using PLI as a future measurement tool in offshore wind farms. Therefore, I tried to provide insights about implementing PLI and criticality assessment in offshore wind farms and clarify the benefits and challenges of using PLI and criticality assessment.

5.2 Selection of method

The approach used for criticality assessment in this sector will consider three steps: PLI estimation, RUL estimation, and criticality assessment rating system.

5.2.1 PLI Estimation

PLI is one of the key performance indicators (KPIs) (Rødseth et al., 2020). It contributes to improving the planning process between the maintenance and the production function in asset management by analyzing the consequences of a failure resulting from the asset's performance degradation (Okafor, 2022; Rødseth et al., 2020) . PLI estimation data can be decided by a plant manager or a cost engineer who is familiar with assets and their operating and environmental conditions (Okafor, 2022; Rødseth et al., 2020). The value of PLI can be calculated according to the following equation:

PLI value = The cost resulting from Quality loss + The cost resulting from Performance loss + The cost resulting from Availability loss

Where type of loss:

5.2.1.1 Availability Losses

Availability losses denote the losses resulting from equipment failure, planned maintenance activities performance, and repair and restoration time (Okafor, 2022). The operational availability of a system, equipment, or asset is a function of its operating time, and it is expressed as:

Availability = (Total Operational Hours - Downtime) / Total Operational Hours

where operational Hours refer to the planned production time.

downtime is the time when a system, equipment, or asset is out of service or unable to perform its function due to unplanned downtime (caused by equipment malfunctions/breakdowns, environmental factors, or human errors) or planned downtime (result from services for maintenance, repairs, restoration, or other planned activities).

Availability loss = lost revenue due to the downtime + replacement/restoration cost+ Maintenance labor costs

5.2.1.2 Performance Losses

Performance losses indicate a decrease in the efficiency of a system due to several factors such as equipment degradation, suboptimal operating conditions, or inadequate maintenance practices (Okafor, 2022). In addition, performance losses can occur due to defects in production operations or unavailability of critical equipment. it is expressed as :

Performance Losses = (No. of work hours due to performance loss x cost of producing during performance loss period)

where performance considers Idling, Minor Stops, and Reduced Speed (Okafor, 2022).

5.2.1.3 Quality losses

Quality losses indicate any deviation from expected quality standards in the products or processes of an organization (Okafor, 2022). In Offshore wind farms, it should identify the expected production capacity of the turbine in order to determine the reasons. Capacity losses typically happen due to:

Defects in the manufacturing, assembly, or installation processes of components.

Poor maintenance practices due to unreliable data provided by monitoring systems and sensors.

Non-documentation of inspections, maintenance activities, or performance data, which makes traceability, and effective analysis for continuous improvement and problem resolution difficult.

Quality loss is expressed as: Quality loss = cost of production per hour during the performance degradation period.

In the case of offshore wind farms, the quality losses can be expressed as Capacity losses or Quantity loss.

5.2.2 RUL Estimation

Remaining useful life (RUL) refers to the time or number of remaining years that a component, or system is able to function in accordance with its intended purpose before malfunction (Karki & Porras, 2021; Okafor, 2022). The RUL of critical components of offshore wind turbines(e.g., blades, gearboxes, generators, and electrical systems) could be estimated by calculating the anomaly degree (AD) of the equipment (Xia & Zou, 2023). Digital techniques such as machine learning and artificial intelligence can be used to analyze data, and thus identify patterns that might refer to potential problems, such as a decrease in efficiency or an increase in vibration levels (Xia & Zou, 2023). An increasing AD will be a signal of increasing the probability of equipment failure (Rødseth et al., 2020).

5.2.3 Criticality assessment

When both the probability and the consequences have been evaluated for a future malfunction of a component, the criticality assessment can be carried out in a risk matrix (Rødseth et al., 2020). Table 3 presents a proposed model of risk matrix that supports the decision-making and planning of preventive work orders . In the consequence category, the PLI is established for the asset and classified as "low, medium, or high "(Rødseth et al., 2020). The probability category is evaluated with the RUL of the component based on anomaly degree (AD) (Okafor, 2022; Rødseth et al., 2020). Trending the RUL in the risk matrix allows for evaluating the right time for performing maintenance activities, and the possible costs and consequences of each failure (Okafor, 2022; Rødseth et al., 2020).

The color code is following a traffic-light logic; if the component is in a green zone, no further actions are necessary (the maintenance actions will be executed in the planned time) (Rødseth et al., 2020). If the component is in a yellow zone, that refers to an early warning where maintenance actions should be carried out (Rødseth et al., 2020). while, when the component is located in the red zone, this serves as an alarm of the need to implement immediate maintenance actions due to the extremely high failure mode that occurred and resulted in a dangerous event. In addition to the color-code system, it is possible for marking each field in the matrix with a number indicating a priority number (Rødseth et al., 2020). Priority number can use in case there are many critical components in the system or the system consists of many subsystems such as in offshore wind farms which consist of several turbines, and each turbine includes critical components (Gearbox, Generator, Blades, Electrical system), that enables to prioritizing which component/ turbine that should be maintained first.

PLI / RUL	PLI=Low	PLI=Low, Medium	PLI= Medium	PLI=Medium, High	PLI=High
Very short					
Short					
Medium				Alarm ↑	
Long				Early warning	

Normal (no action)　　Early warning　　Alarm

Table 3 Risk matrixas criticality assessment for component /turbine

5.2.4 PLI Cube

The Profit Loss Indicator (PLI) Cube is an approach for calculating PLI at the process, plant, system, or equipment level, where PLI is the sum of loss in turnover and loss in extra costs. It provides an evaluation of the financial impact resulting from component failures, allowing to prioritize the components, as well as perform a holistic analysis of maintenance planning and resource allocation based on financial considerations. It also contributes to creating room for future improvements by revealing other contributed elements of lost profits in production such as environmental and safety impacts. The PLI Cube is made up of three primary dimensions. The first dimension is about the individual components or assets. The second dimension represents accounting where it could be differentiated between turnover loss and extra costs. The last dimension represents time losses and waste.

The financial considerations involve production loss, repair and maintenance costs, revenue impacts, and other costs related to the failure of each component and its failure mode. Production losses usually resulted from components unavailability, decreased efficiency of the components, or less amount of production. Furthermore, to calculate the maintenance cost, the following costs should be included costs of resources. The costs of resources involve hiring transportation, personnel, and spare parts. Sometimes the maintenance requires specific means like a crane for lifting, and a helicopter which is used when there is no ability to access the offshore wind sites. In addition, the cost of equipping offshore wind farms with advanced sensors. The waste consideration is classified into the category of "utilization", "raw material" and "resource consumption". Waste refers to the misuse of resources such as energy, materials, and time. The main parameters in PLI Cube, in the case of applying it in offshore wind farms, are formulated below:

The time losses due to component /turbine unavailability, the poor performance of component /turbine, and /or low capacity in production are formulated below

Profit Loss = Turnover Loss + Extra costs

OEEavailability = OEE.A,T + OEE.A,C

OEEperformance = OEE.P,T + OEE.P,C

OEEquality = OEE.Q,T + OEE.Q,C

Where : OEE.A,T = OEE's Availability (Time) loss due to Turnover loss in production

OEE.A,C = OEE's Availability (Time) loss due to Extra Cost resulting from downtime

The profit loss due to the waste can be calculated :

Profit Loss = Turnover Loss + Extra costs

U = W.U,T + W.U,C

RM = W.RM,T + W.RM,C

RC = W.RC,T + W.RC,C

OW = W.OW,T + W.OW,C

Where W.U,T = Time loss during performing maintenance (in the case of a maintenance task that is not necessary)

W.U,C = Extra Cost due to performing maintenance

The Figure 13 below shows the PLI cube

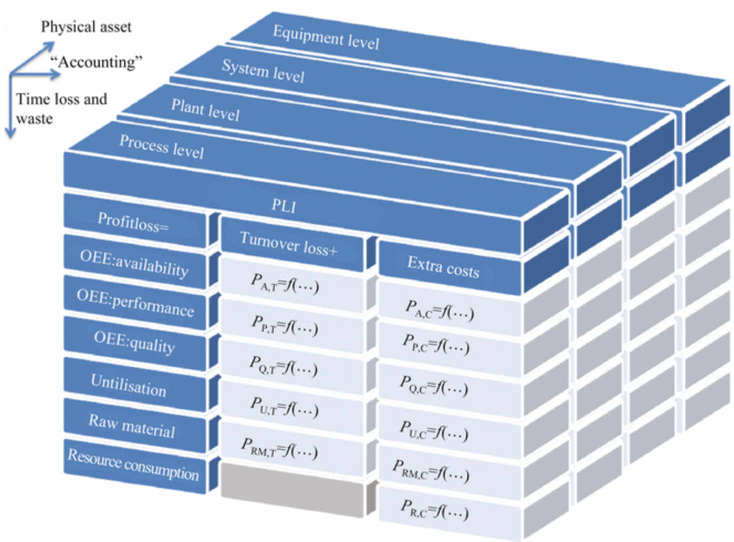

Figure 13 PLI cube (Rødseth et al., 2015)

Chapter 6

Results

6.1 Application of Digital technologies in offshore wind farms

High O&M costs are regarded as one of the main challenges which restrict the development of offshore wind energy. Therefore, an O&M strategy based on condition monitoring can assist to optimize O&M schedules and minimize O&M costs resulting from equipment failures and unplanned repair effectively. Furthermore, the use of digital technologies contributes to enhancing performance and improving decision-making. These technologies provide the capability to monitor the current state of the system and its critical components, collect data from various sources, and analyze data by using advanced analytics techniques like machine learning and artificial intelligence in order to recognize patterns and anomalies, and thus predict failure and the right time to perform maintenance. This approach enables optimized decisions regarding maintenance, asset management, workers' safety, and marine ecology safety.

The monitoring techniques that are widely utilized in offshore wind farms involve acoustic monitoring, thermography, visual inspection, Oil analysis, vibration monitoring, strain monitoring, etc. Acoustic monitoring techniques include acoustic emission techniques and ultrasonic detection techniques, which are able to detect abnormal sounds in different components. The technique is considered a very efficient means to observe internal damage. For example, deviations from normal sounds are usually caused by mechanical overloading in the gearbox and damage to blades (Xia & Zou, 2023). In addition, applying the thermography technique to the blade assists to reveal material damage and fatigue based on changes in thermal diffusivity. Visual inspections are effective in examining visible damages in critical components in the turbine. As well, the use of advanced vision technology for condition monitoring of OWFs is becoming popular. Through using the drone, it becomes possible to collect digital images of OWF damage, as well as determine the extent and locations of damages in OWFs. Strain detection techniques can detect microscopic changes at locations and anticipate the occurrence of damage based on structural deformation, and check if this structural deformation exceeds the deformation in the record (deformation in the record is the threshold). Vibration monitoring and oil analysis of the generator, gearbox, and bearings of a wind turbine are common operations that supply information on the deterioration state. The data gathered by monitoring techniques will be processed via AI algorithms to detect anomalies and thus predict the remaining life of each component of the wind farm, and provide early warning of possible failures. The monitoring system also provides timely warnings of unexpected hazards, such as bad weather conditions, high impacts on marine wildlife, and Cable failures which can lead to electrical risk, etc. That helps to manage personnel safety and marine ecology. The digital twin model enables real-time monitoring of OWFs, which allows wind farm operators to detect failure before it happens, and take low-cost, highly reliable, safe, and environmentally friendly O&M decisions. Furthermore, that helps to optimize the design of future wind turbines, which enhances sustainability.

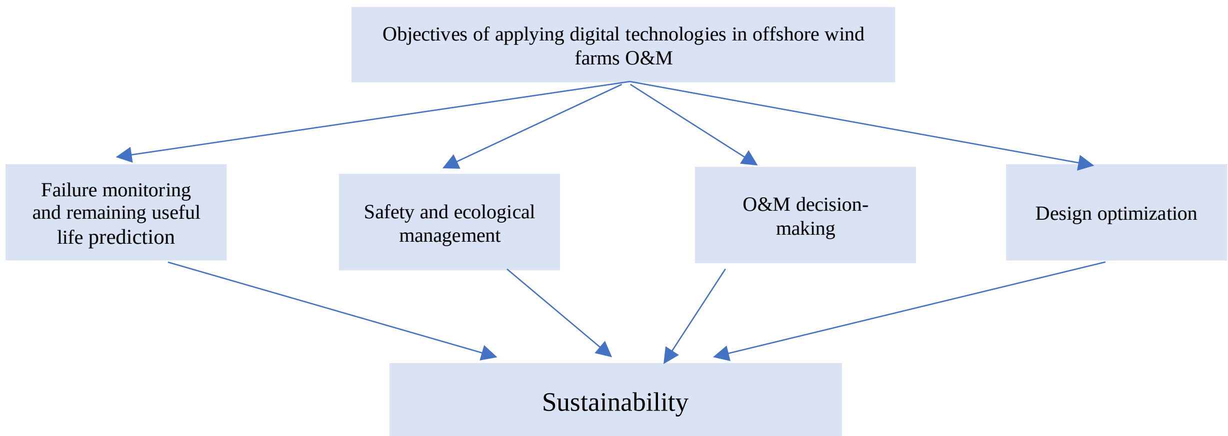

Figure 14 Objectives of applying digital technologies in offshore wind farms O&M

6.2 Criticality assessment in offshore wind farms

Applying the criticality assessment in offshore wind farms contributes to evaluating the likelihood, impact, and failure consequences of each component in the turbine, thus prioritizing the components based on their importance, impact, and criticality to the overall operation and performance of the wind farm. This will assist to prioritize the maintenance and investment decisions, allocate resources efficiently, evaluate the right time for executing preventive maintenance work orders, and decrease the risks associated with asset failure or degradation, thus improving maintenance planning and reducing unplanned costs. Hence, the criticality assessment will be an essential element to ensure the reliability, safety, and performance of the offshore wind farm. Due to the difficulty of obtaining information about maintenance and repair costs, and the anomaly degree for each component in offshore wind farms, where such data tend to be confidential. Therefore, a scenario for a critical component such as turbine blades in offshore wind farms has been created to explain the role of criticality assessment in decision-making.

- **Scenario: Turbine Blades**

Step 1: PLI estimation

The malfunction was first observed when significant reduction in power generation capacity. A capacity audit meeting evaluated the economic loss and revenue loss due to this reduction. In addition, maintenance personnel conducted an inspection of the blades and found that the cause of this situation was increased wear and tear on the blades which led to cracks exceeding the limited permissible for cracks. The partial replacement was performed, and the maintenance time totaled 50 hours with downtime according to (Du, 2017). Table 4 summarizes the different types of losses that happened due to this situation:

Situation	Type of loss
Reduction in power generation capacity	Capacity loss
Capacity audit meeting	Capacity loss
Maintenance personnel cost	Availability loss
Partial replacement of blades	Availability loss
Revenue loss	Availability loss

Table 4 the different types of losses

PLI value /NOK= sum of the cost resulting from Capacity loss and Availability loss.

The PLI value could be Low,Medium, High where reduced power generation capacity directly impacts revenue generation, as well as repairing damaged turbine blades incurs significant expenses.

PLI values represent the costs that will be the consequence of equipment failures. These consequences include safety risks, production Interruptions, environmental impact, financial losses, and the extent of the impact on overall wind farm operations. Based on the scenario of turbine blades, blade failure leads to safety hazards for personnel and surrounding areas, as well as blade fragments impact negatively the marine ecosystem. In addition, blade failure causes partial/complete loss of production which requires replacement. The consequences estimation of failure helps to classify various components according to severity classes with corresponding PLI values for decision-making. Table 5 below illustrates risk ranking

Rank	Class	PLI	Description
1	Minor	NOK	Failure leads to a minor loss of production due to minor system damage. Minor repair/inspection is required
2	Major	NOK	Failure leads to a partial loss of production with no personal injuries and minor effects on the environment. Major repair/ Partial replacement is required. The alarm should be activated.
3	Critical	NOK	Failure leads to complete loss of production with the likelihood of personnel injuries risk and major effects on the environment. Specific tools are required in maintenance. Partial/complete replacement is required. Specific tools are required in maintenance The alarm should be activated.
4	Catastrophic	NOK	Failure leads to production stops with the likelihood of personnel injuries/Death and major effects on the environment. Complete replacement is required. Specific tools are required in maintenance. The alarm should be activated.

Table 5 Risk ranking

Step 2 The Remaining Useful Life (RUL) estimation

The Remaining Useful Life (RUL) of offshore wind turbines can be predicted by techniques that use data from sensors and other sources. This assists to take proactive actions to prevent breakdowns and prolongs the RUL of the turbines, thus reducing the performance deterioration of assets and O&M costs over time. So, RUL estimation is an essential element in the Criticality Assessment in order to optimize decision-making in maintenance planning and asset management.

In order to achieve systematic failure monitoring, risk management, and O&M optimization of offshore wind farms, various data (for example sensor measurements, operation and maintenance records, weather records, physical experiments, failure events) must be collected for a specific period. Then, data should be treated and analyzed using big statistical analysis techniques to extract features that can regard as indicators of the turbine's health and degradation. For example, obtained anomaly degree describes the difference between the target observation and normal samples (Rødseth et al., 2020). After that, it is possible to build a trained model that can help operators to anticipate the remaining useful life of individual turbines based on sensor readings. The model takes the current or historical data as input to evaluate how much longer the turbine is expected to function before requiring maintenance or replacement. Table 6 illustrates the relationship between the remaining useful life (RUL) and anomaly degree (AD).

AD	**RUL**	**Description**
Beginning anomaly	Long	Degradation of critical components will be extremely low, minor repairs or inspection can be performed during system operations or during planned maintenance.
Low degree of anomaly	Medium	Degradation of critical components will be moderate, minor repairs can be performed during system operations or during planned maintenance.

Medium degree of anomaly	Short	Degradation of critical components will be high which leads to a shutdown of the system to perform a partial replacement or major repair, thus loss of production and an increase in safety losses.
High degree of anomaly	Very short	The critical component is out of service which leads to a shutdown of the system to perform a complete replacement, thus production stops and an increase in safety losses.

Table 6 Relationship between RUL and AD

Based on the scenario of turbine blades and the Table of the relationship between AD and RUL, historical data and failure records indicate anomaly degree, in this case, could be medium, thus RUL will be short.

Step 3 Criticality Assessment

The criticality assessment of an asset can be executed in a risk matrix when both the probability (RUL) and the consequence of a possible malfunction of an asset or parts of the equipment (PLI) are evaluated. Risk will be expressed as:

Risk = Probability (P) x Consequence (C)

where P is defined as the probability that a component will break down due to its RUL, where the lower the remaining useful life, the higher the probability of failure. To assess the likelihood of failure occurring for each critical component, it should be considered several factors such as historical failure data, maintenance records, environmental conditions, and component reliability. C is defined as the Consequences due to the malfunction of the asset (PLI) such as safety risks, complete/partial production loss, environmental impact, financial losses, and the extent of the impact on other components in the wind farm. In offshore wind turbines, the turbine is made up of several components, thus the risk of the turbine will be calculated as:

Risk = P1C1+ P2C2+….+PnCn $=\sum_{i=1}^{n} Pi * Ci$

In addition, the risk of offshore wind farm will be calculated as:

$$The\ total\ risk\ in\ offshore\ wind\ farm\ = \sum_{j=1}^{k} \sum_{i=1}^{n} Pi * Ci$$

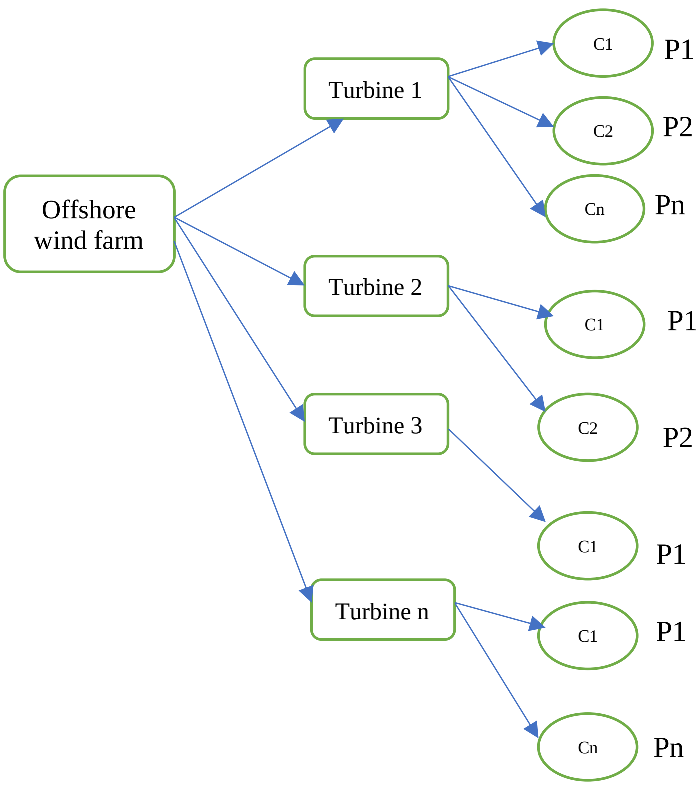

Figure 15 Risk Analysis

The main purpose of a criticality assessment of physical assets in offshore wind farms is to identify the critical components in the turbines/critical turbines in offshore wind farms which have an impact on operations, safety, and availability. This will help to take convenient maintenance measures and allocate resources in order to minimize unplanned downtime resulting from frequent maintenance activities that lead to financial losses (O&M costs, production loss).

Based on the scenario of turbine blades, the PLI value is classified as“medium, high”, and RUL is classified as "short". Thus blades are located in the red zone of the risk matrix, where immediate maintenance actions should be performed to address erosion and damage promptly.

To avoid the frequent occurrence of critical situations of blades:

- Blades should be equipped with advanced imaging or monitoring systems to detect early defects.

- It should be used Corrosion-resistant materials in the design of the blades to improve durability.
- Establishing contingency plans and spare blade inventory to reduce downtime, and ensure timely repairs

Benefits of Applying Criticality Assessment of Physical Assets in maintenance planning in offshore wind farms

The main purpose of a criticality assessment of assets in offshore wind farms is to maximize the availability of crucial components by optimizing maintenance planning which can lead to avoiding unplanned downtime and minimizing financial losses (O&M costs, production loss). Other advantages of criticality assessment of assets include:

Risk Mitigation

The offshore wind turbines are exposed to bad weather conditions such as strong winds and saltwater which make some components vulnerable to corrosion or faults/ breakdowns. Moreover, offshore wind farms are spread over large areas, making maintenance logistics complex and costly due to the difficulty of accessing sites to carry out maintenance activities, especially in harsh marine conditions. The criticality assessment contributes to identifying the critical components in the turbines/critical turbines in offshore wind farms through data analytics. This allows making decisions relating to the choice of convenient arrangements and measures, including maintenance action, strategies, optimal inspection intervals, and optimal allocation of resources such as vessels, crew, and equipment. Furthermore, this helps to mitigate the risk and consequences of unexpected failures and downtime, as well as lower overall maintenance costs and minimize the likelihood of safety incidents or environmental impacts.

Planning and Long-Term Asset Management:

Since offshore wind farms have long lifetimes, effective asset management is significant in managing maintenance functions in order to enhance asset-sustained operations. A criticality assessment is used as a base for long-term asset management planning. By regularly reviewing and continuously updating the assessment, organizations and stakeholders can adapt to changing conditions, reassess priorities, and ensure that maintenance strategies are still convenient with business goals and needs. Furthermore, the criticality assessment will allow maintenance planners to make efficient decisions on the prioritization of work orders based on balancing costs, risks, and performance. This would help in reducing time losses resulting from unplanned maintenance activities and frequent visits to sites. This will minimize costs, increase personnel safety, and reduce the environmental risks associated with maintenance operations. So, the criticality assessment of equipment will be an effective method in maintenance planning in order to enhance sustainability (Rødseth et al., 2020).

6.3 PLI Cube

Turnover losses

Turnover losses in the offshore wind sector refer to financial losses resulting from reduced revenue due to outages or reduced energy production. These losses can impact the profitability and return on investment of the wind farm, thus affecting financial sustainability. Turnover losses in offshore wind farms return to many causes :

- Component Failures: the component failures affect its performance, which leads to minimizing energy production, potentially decreasing the availability of offshore wind turbines. These failures can be caused by factors like corrosion, degradation, manufacturing defects, or poor maintenance. The degree of failure and the criticality of the failed component affect the quantity of produced energy, where repairing or replacing the faulty components requires a long time which can result in turbine downtime, thus increasing the turnover losses.
- Maintenance Strategies: If maintenance activities are not scheduled and performed successfully, it can result in unexpected breakdowns and unplanned downtime.
- Weather-Related Factors: Offshore wind farms are located in areas where harsh weather conditions like strong winds, storms, and rough seas. When the wind speed exceeds the

required speed, the turbine shutdowns for safety reasons which results in stopping production. Furthermore, bad weather causes delays in maintenance and repair actions due to the difficulty of accessibility and logistics.

- Delays in component deliveries or unavailability of resources.
- Human Error: poor repair or insufficient inspection leads to energy waste. That returns to inappropriate training of personnel, as well as not giving enough time to correctly perform the repair or the inspection.

Extra costs

The extra costs are related to various aspects of offshore wind farm development, construction, operation, and maintenance. These costs involve project financial investment, foundation and Installation Costs, production costs, O&M costs including inspections, servicing, repairs, component replacements, and personnel costs, as well as spare parts costs and transportation. Furthermore, costs associated with installing and operating the monitoring systems, which consider essential to ensure the safety of both wild marine life and human, as well as the performance of critical components.

Waste

Reducing waste in the production and operational processes is important to ensure efficient and sustainable operations and optimize economic viability. The waste is produced from the misuse of energy, materials, and time.

- Waste of energy : It occurs due to Inefficient turbine operation that returns to many reasons such as poor maintenance or poor performance monitoring. The degradation of transmission infrastructure can lead to a loss of energy during the transmission of electricity.
- Waste of Materials: It involves insufficient resource allocation, such as human resources, equipment, and spare parts. In addition, inefficient material management, including planning and use of materials.

- Waste of Time: It occurs due to Unscheduled downtime, delays in maintenance activities or repair actions due to bad weather conditions, waiting for equipment/logistics availability, or unnecessary visits to the sites to perform maintenance where there is no need to carry out maintenance.

According to the Scenario of turbine blades, the profit loss has occurred due to the wear and tear on the blades which led to cracks exceeding the limited permissible for cracks. That led to minimizing energy production because of the reduction in the performance of the blade. The availability of offshore wind turbines will be affected by unplanned downtime to execute maintenance. All of that will cause the occurrence of revenue loss. Moreover, performing partial replacement will result in extra costs associated with the existence of spare parts, qualified staff, and specific tools like a crane, as well as the disposal and recycling of broken blades cause environmental problems. The most significant factor that should take into consideration is the weather conditions, whether there is accessibility to sites or not, in order to avoid the waste of time and revenue loss which affect the financial sustainability of offshore wind farms.

Benefits of Applying PLI cube in offshore wind farms

The use of PLI cube in offshore wind farms will allow the operators to calculate the time losses and wastes, which can help to detect other elements that impact lost profits in production, as well as create room for future improvements. The following points clarify the benefits of using a PLI cube as a performance measurement tool in offshore wind farms:

- Financial Performance Assessment: It allows wind farm operators to track and analyze the factors that affect revenue, cost, and profitability. This can contribute to identifying areas for improvement, thus optimizing the revenue and financial returns.
- Cost Management: Effective cost management is essential for achieving the financial success and sustainability of offshore wind farms. The PLI cube enables operators to analyze different costs such as maintenance costs. By adopting efficient maintenance strategies, it is possible to optimize resource allocation and minimize the maintenance costs

- Resource Utilization Optimization: The utilization in the PLI cube focuses on turbine availability, operational efficiency, maintenance optimization, and waste reduction. That will contribute to improving operational performance and financial returns.
- Decision Support: The PLI cube considers a valuable decision support tool for wind farm operators. It provides insights into financial performance indicators, enabling operators to make decisions based on data. That will assist in resource allocation effectively, maintenance optimization, and cost management, leading to improved financial outcomes and long-term continuation.

Chapter 7

Discussion

Offshore wind farms are one of the renewable energy resources that generate efficient and environment-friendly energy. They provide promising solutions to move forward to a more sustainable energy system. However, there are several challenges that prevent offshore wind farms to achieve their potential such as the high O&M cost, their existence in a harsh marine environment which affects their availability, their negative impacts on marine ecosystems and wildlife, and high risks that threaten the safety of offshore O&M workers. Therefore, it is necessary to take appropriate measures in order to overcome these challenges and achieve a successful and sustainable transition to offshore wind. These measures, including the digitalization of maintenance services and using effective measurement tools like the Profit Loss Indicator cube (PLI), contribute to decreasing operation and maintenance (O&M) costs while maximizing availability, quality, and economic benefits, all while minimizing negative impacts on the safety and the environment.

7.1 Digitalization

Digitalization is a significant approach to making maintenance strategies more sustainable in offshore wind farms. The use of digitalization technologies, such as sensors, the Internet of Things (IoT), artificial intelligence (AI), and big data analytics, will contribute to improving the maintenance and prolonging the asset lifespan by monitoring the health and condition of the equipment. This can help to detect failures early, diagnose anomalies, and troubleshoot faults at the location and remotely. That leads to improving efficiency by minimizing shutdown, increasing energy production, and optimizing maintenance decision-making, additionally, providing new suggestions for designing the components.

Digitalization technologies for failure monitoring and remaining useful life (RUL) prediction

Given the complex components of OWFs which are typically vulnerable to failure due to harsh marine environments, therefore, their O&M costs will be very expensive because of logistics, resources, and specific tools such as external crane vessels. Thus, the use of digital techniques in offshore wind farms can be effective. The advanced sensors, which are installed on the critical components of the system, provide the ability to continuously observe components' performance and collect data. Digital twins can be also utilized to support real-time monitoring and failure diagnosis of offshore wind farms. Machine learning algorithms, or artificial intelligence algorithms process and analyze the gathered data to identify patterns that may indicate the beginning of failure or degradation. The output resulting from the analysis can be used to anticipate the remaining useful life of the critical components and determine the reasons that lead to failure. This can help to determine the turbines/components with anomalies. This allows operators to create a maintenance action plan according to the anomaly degree level where some equipment/turbines with anomalies should be prioritized before others.

Digitalization technologies for safety and ecological management

Since the construction and operation of offshore wind farms have many negative impacts on operator safety and marine ecology, the application of digital techniques enhances safety and ecological management in offshore wind farms. Digital sensors and monitoring systems provide the capability to observe regularly the wind turbines, electrical systems, weather, and environmental conditions in offshore wind farms. This real-time monitoring allows operators to discover possible hazards, such as high wind speeds, icing, or equipment failure, thus taking immediate actions to minimize the risk of accidents and environmental damage. Furthermore, some of the digital technics could be integrated together like Digital twins, robotics, drones, and cameras to achieve remote monitoring and self-maintenance of offshore wind farms. This approach considers effective and promising because it can ensure operators' safety and protect them from exposure to dangerous environments, as well as minimizes the need for human intervention.

Digital technologies are also taking part in the area of marine eco-management by establishing models and simulations to detect changes in environmental conditions in the area around offshore wind farms and seabed. The changes are usually resulting from oil spills, pollution, noise, and transportation associated with maintenance. Digital sensors and monitoring systems can be used to test water quality and evaluate environmental parameters in order to execute effective measures to mitigate the impact of offshore wind farms on the ecological system, as well as observe the movement of ships and helicopters to avert collision risks that threaten marine wildlife.

Digital technologies for O&M decision-making

Digital technologies have a significant role in O&M (Operations and Maintenance) decision-making in offshore wind farms. Digital techniques assist to anticipate when equipment is likely to fail, and also determine the remaining life of an offshore wind turbine. The digital twin (DT) model can supply a virtual environment for maintenance path planning. Hence, applying digital twin (DT) technology with machine learning techniques can be efficient and provide insights and recommendations to optimize the accuracy of decision-making about equipment replacement and asset management, as well as build a maintenance plan with higher reliability. Digital technologies have also effects on the design optimization of offshore wind farms. These technologies can help designers and operators optimize the selection and positioning of turbines where energy production can be maximized, and the impact on marine wildlife can be minimized through analyzing data related to wind speeds, currents, and environmental factors. For example, adopting digital twins technology allows utilizing a set of data from current projects for establishing a virtual twin model of OWFs. Subsequently, the dynamic simulation of designs can be executed with the aim of determining areas for improvement in the design, avoiding the demerits that can lead to unwanted issues, thus improving efficiency and profitability (Xia & Zou, 2023). Furthermore, digital technologies enable a wider range of societal sectors such as designers, operators, and stakeholders to engage and collaborate in the design and management of offshore wind farms, which can lead to consolidating the goals, improving future design efficiency, and allocating the required operation and maintenance resources based on historical O&M data.

Challenges

Despite the significant benefits that can achieve by adopting digitalization in the maintenance process, there are also lots of potential challenges that face digitalization including technological complexity, Increased energy consumption to operate, high capital investments, data privacy, and Inequality distribution of benefits.

Not all companies have the capability to carry out the digital transformation of their maintenance services due to technological complexity which require qualified staff with knowledge and digital skills to understand effective implementation strategies, and additional costs to train human labor to adapt to digital culture (Raj et al., 2020). The use of digital tools also demands high initial investments. To mitigate this cost, it is preferable to use the monitor devices for the critical components that have an impact on the system (downtime, availability, reliability). Utilizing a large number of these devices will generate a huge amount of data, which can lead to interference and decreased data quality and give erroneous information, thus less effective decision-making and increased operational costs. Moreover, digitalization could create social inequalities, and lead to an increase in poverty, unemployment, and an aging society because of minimizing human intervention (Raj et al., 2020). Companies should also take data privacy and security into account, and protect it from leaks and hackers. Therefore, to guarantee the sustainable development of the offshore wind field, the benefits and challenges of digitalization in maintenance strategies should be considered carefully.

7.2 The most favorable and cost-efficient maintenance of offshore wind farms

As the importance of offshore wind farms increases and their fast expansion, a corrective maintenance strategy considers non-suitable due to the consequences resulting from relying on it such as prolonged downtime, less availability of turbines, and high costs related to logistics, emergency repairs, and equipment replacement. Therefore, combining predictive maintenance and predetermined maintenance is considered the most favorable and cost-efficient maintenance of offshore wind farms. Predetermined maintenance ensures performing regular inspections and maintenance services at predetermined intervals based on manufacturer recommendations, and historical data. Predictive maintenance enables operators to monitor the degree of deterioration or anomalies by leveraging real-time data and monitoring systems. Thereby, maintenance planning will be done based on the level of an anomaly degree of critical components and their consequences. Maintenance requirements will be prioritized according to the specific needs of each component, which lead to optimizing resource utilization and energy production, as well as minimizing both unnecessary costs and environmental impact. Furthermore, predictive maintenance, by using advanced analytics, helps prevent major failures and reduces the need for emergency repairs and frequent visits to the locations thus, maximize energy production. That will increase the overall reliability of wind turbines, and minimize both downtime and maintenance costs. This approach can contribute to mitigating risks that threaten marine ecology by reducing maintenance waste and decreasing the noise resulting from transportation and maintenance practices. Furthermore, it enhances personnel safety by minimizing unnecessary maintenance activities, especially during harsh marine conditions.

Despite predictive maintenance requiring a high investment initial cost due to automated and advanced devices, predictive maintenance strategies can ensure the continuation of offshore wind farms as a renewable energy source.

7.3 Criticality assessment and PLI cube in offshore wind farms

To unlock offshore wind growth and sustainability, it should determine the critical components that have an impact on safety, reliability, and overall operational performance. It should also identify the consequences resulting from each failure, as well as measure time losses and wastes. Criticality assessment and PLI cube are effective measurement methods that enable operators' efficient decision-making process in maintenance planning.

Criticality assessment, through evaluating the anomaly, contributes to classifying components in offshore wind farms into three categories:

- Components that their failures may cause risks to personnel, the environment, or the wind farm infrastructure.
- Components that demand more frequent inspections, proactive maintenance, and timely replacements.
- Components that have an impact on overall operational performance, and lead to long downtime.

In addition, the use of a PLI cube enables assessing the financial performance of offshore wind farms by calculating lost income, revenue, and cost, as well as evaluating the financial impacts of consequences resulting from the occurrence of failures. By using the PLI cube, it is possible to perform a comprehensive financial study of components, operations, or the overall system. This can occur through tracing and measuring time losses and various causes of waste. Therefore, Criticality assessment and the PLI cube can be regarded as elements that contribute to the development and sustainability of offshore wind farms. Criticality assessment will help to manage risk effectively by prioritizing maintenance activities and allocating resources. It allows operators to plan maintenance based on the maintenance needs, and risks related to the critical components in order to minimize the likelihood of accidents or environmental impacts. The PLI cube enables operators to perform financial analysis, reveal the elements affected by waste and time losses, and support decisions. This can contribute to optimizing revenue, cost management, and resource utilization efficiency.

Despite the benefits of applying criticality assessment and the PLI cube in offshore wind farms, there are some challenges to consider. The utilization of criticality assessment and the PLI requires qualified operators that have the knowledge to perform effective analysis to make proper decisions. The other issue is the accuracy and availability of data, where insufficient or unreliable data can limit the accuracy of the assessments and impact negatively the decision-making process.

The using of criticality assessment and the PLI cube in offshore wind farms can enhance the development, operational performance, and financial viability of offshore wind farms. Therefore, the challenges should be addressed, and the benefits should be leveraged to achieve sustainability in this sector.

7.4 The future of maintenance in offshore wind farms

The offshore wind sector is growing and expanding globally. This sector has proven its ability to meet energy needs during the Covid-19 pandemic, as well as during the energy crisis resulting from the war in Ukraine. Offshore wind farms play a vital role in producing clean, renewable energy without greenhouse gas emissions. This generated power can be utilized to produce hydrogen and synthetic fuels in a climate-friendly way. In recent years, many efforts are done to reduce the cost related to investment and deployment in order to adopt sustainable energy produced from wind farms and decrease the dependency on fossil fuels. It is expected the future of offshore wind farms will be promising due to the digitalization of maintenance services. Digital technologies will contribute to a transition to Sustainability-Oriented Maintenance. There is a focus on improving maintenance practices in order to increase production. Digital technologies allow operators to get information about the performance and capacity of each turbine in the offshore wind farm. If the operators detect any anomaly, such as changes in temperature, vibration, oil quality, or electrical performance, they will determine maintenance needs based on conditions, and related issues will be addressed before failures occur to ensure efficient turbine operation. This also assists to allocate resources; including manpower, spare parts, and equipment; more effectively, which leads to minimizing maintenance waste and reducing unnecessary costs resulting from the frequent visits to the sites. The future of offshore wind farm maintenance will witness the use of robotics and drones (Golysheva, 2021). It is expected to utilize robots equipped with advanced sensors for inspection, maintenance, and repair tasks. These robots can contribute to enhancing safety by revealing anomalies autonomously, as well as carrying up routine maintenance activities without human intervention. Drones also can perform visual inspections of turbine blades in the case of bad weather conditions . This helps to protect staff from hazards as well as minimize logistical costs. Automated marine robotics are new innovations equipped with scanners that are used to detect anomalies in substructures and cables (Golysheva, 2021). They can use also in the cleaning and checking process. All of the technologies, used in offshore wind farms, will direct attention to focus more to develop the turbine design in order to suit the operational requirements and choosing materials that are eco-friendly and more resistant to hard marine conditions (Golysheva, 2021).

The integration between these digital technologies and the (PLI) cube as a measurement tool will enable operators to optimize asset management by providing economic feasibility of the consequences resulting from each failure. Thus, this will assist them to protect their investments, making proper decisions, and orienting maintenance practices to achieve business objectives and sustainability targets. This integration can help to enhance the overall efficiency, profitability, and sustainability of offshore wind farms.

Chapter 8

Conclusions and Recommendations for further work

8.1 Conclusions

Offshore wind farms consider crucial contributors to addressing climate change and moving towards a sustainable future through their role in producing clean and renewable energy. Maintenance is one of the significant factors to ensure the safe and reliable operation of offshore wind farms. However, the maintenance faces unique challenges due to offshore wind farms' remote and harsh environments, High maintenance costs, inefficient data management, unexpected failures, aging, safety, and environmental consideration. Therefore, the whole essence of this report is to clarify the contribution of digital technologies, criticality assessment, and PLI estimation in overcoming maintenance challenges by improving maintenance planning and achieving sustainability objectives in offshore wind farms. The application of criticality assessment with the application of both PLI as well as anomaly degree calculation in offshore wind farms has been proposed. The findings have highlighted the benefits of the proposed system in decision-making operations, prioritizing maintenance activities based on the impact of component failures, utilizing resources effectively, and minimizing revenue losses associated with downtime. The findings have also illustrated that the evaluation of anomaly degree (AD) by using AI algorithms as well as PLI calculations will help to assess the consequences associated with asset failure. This will enable operators to create a work priority system. In this work system, maintenance activities will prioritize based on the anomaly degree of each critical component/turbine, and the impact of this anomaly on the financial aspect, environment, the overall performance, efficiency, and safety of the wind farm. Utilizing digital techniques in offshore wind farms will contribute to improving offshore wind farm maintenance planning to be more proactive, cost-effective, and efficient. Maintenance planning will be done depending on data-driven, real-time monitoring, and advanced analytics. These techniques will also assist maximize the availability and lifespan of offshore wind turbines while minimizing costs and environmental impacts, resulting in achieving sustainability.

8.2 Recommendations for Further Work

Based on the conclusions presented above, the following recommendations are made:

1. More investigations with case studies should be done to explore the impact of the implementation of criticality assessment and PLI estimation in real-world offshore wind farm operations. Field studies and case analyses can provide valuable insights into the practical application of these tools and their impact on maintenance planning and sustainability outcomes.
2. The long-term impact of incorporating criticality assessment and PLI estimation into maintenance planning should be evaluated. Future studies can assess the financial and sustainability benefits achieved through the implementation of these tools

Bibliography

Abdul R. Beig, S. M. M. (2016). Wind energy [Academic Press]. 60-77.

Al-Turki, U. M., Ayar, T., Yilbas, B. S., Sahin, A. Z., Al-Turki, U. M., Ayar, T., Yilbas, B. S., & Sahin, A. Z. (2014). Health, safety and sustainability in maintenance. *Integrated Maintenance Planning in Manufacturing Systems*, 59-69.

Besnard, F. (2013). *On maintenance optimization for offshore wind farms*. Chalmers Tekniska Hogskola (Sweden).

Catapult. (2022). Offshore wind energy. https://guidetoanoffshorewindfarm.com/wind-farm-costs

CEN. (2010). NS-EN 13306: 2010, Maintenance terminology. In.

Dalgic, Y., Lazakis, I., Dinwoodie, I., McMillan, D., & Revie, M. (2015). Advanced logistics planning for offshore wind farm operation and maintenance activities. *Ocean Engineering*, *101*, 211-226.

Deepa, N., Pham, Q.-V., Nguyen, D. C., Bhattacharya, S., Prabadevi, B., Gadekallu, T. R., Maddikunta, P. K. R., Fang, F., & Pathirana, P. N. (2022). A survey on blockchain for big data: approaches, opportunities, and future directions. *Future Generation Computer Systems*.

Du, M. (2017). An improved FMECA method for wind turbines health management. *Energy and Power Engineering*, *9*(04), 36.

Duc, T. A., Karol, D., & Katarzyna, S. (2018). The Predictive Maintenance Concept in the Maintenance Department of the "Industry 4.0" Production Enterprise. *Foundations of Management*, *10*(1), 283-292.

El-watch. (2023). Sensor. https://el-watch.com/products/

Golysheva, D. E. (2021). How Predictive Maintenance Can Unlock Offshore Wind Growth. *Power transmission engineering*. **https://www.powertransmission.com/articles/1351-how-predictive-maintenance-can-unlock-offshore-wind-growth**

Gonzalo, A. P., Benmessaoud, T., Entezami, M., & Márquez, F. P. G. (2022). Optimal maintenance management of offshore wind turbines by minimizing the costs. *Sustainable Energy Technologies and Assessments*, *52*, 102230.

Government.no. (2023). Nye områder for havvind på norsk sokkel. https://www.regjeringen.no/no/aktuelt/nye-omrader-for-havvind-pa-norsk-sokkel/id2973609/

Haghshenas, A., Hasan, A., Osen, O., & Mikalsen, E. T. (2023). Predictive digital twin for offshore wind farms. *Energy Informatics*, *6*(1), 1-26.

HBMCompany. (2022). Condition monitoring system for offshore wind farms. https://www.hbm.com/en/6089/condition-monitoring-offshore-wind-turbines/

Hersenius, C., & Möller, U. (2011). Operation and Maintenance of offshore wind farms.

J.A. Andrawus, M. o. f. w. t., PhD thesis, Robert Gordon. University, Aberdeen, United Kingdom, . (2008). Maintenance optimization for wind turbines

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

Karki, B. R., & Porras, J. (2021). Digitalization for sustainable maintenance services: A systematic literature review. *Digital Business*, *1*(2), 100011.

Karyotakis, A., & Bucknall, R. (2010). Planned intervention as a maintenance and repair strategy for offshore wind turbines. *Journal of marine engineering & technology*, *9*(1), 27-35.

Li, M., Jiang, X., Carroll, J., & Negenborn, R. R. (2022). A multi-objective maintenance strategy optimization framework for offshore wind farms considering uncertainty. *Applied Energy*, *321*, 119284.

Li, X., Ouelhadj, D., Song, X., Jones, D., Wall, G., Howell, K. E., Igwe, P., Martin, S., Song, D., & Pertin, E. (2016). A decision support system for strategic maintenance planning in offshore wind farms. *Renewable Energy*, *99*, 784-799.

Macchi, M., Farruku, K., Holgado, M., Negri, E., & Panarese, D. (2016). Economic and environmental impact assessment through system dynamics of technology-enhanced maintenance services. *International Journal of Industrial and Systems Engineering*, *23*(1), 36-56.

Meurs, N. (2017). Advanced maintenance operations: For the Delft Offshore Turbine.

Nilsson, J., & Bertling, L. (2007). Maintenance management of wind power systems using condition monitoring systems—life cycle cost analysis for two case studies. *IEEE Transactions on energy conversion*, *22*(1), 223-229.

Okafor, C. (2022). *Performance Measurement using Deep Digital Maintenance (DDM) Concept: A Technique for Measuring" Hidden Factory"* NTNU].

Oztemel, E., & Gursev, S. (2020). Literature review of Industry 4.0 and related technologies. *Journal of Intelligent Manufacturing*, *31*, 127-182.

Poór, P., Ženíšek, D., & Basl, J. (2019). Historical overview of maintenance management strategies: Development from breakdown maintenance to predictive maintenance in accordance with four industrial revolutions. Proceedings of the international conference on industrial engineering and operations management, Pilsen, Czech Republic,

Qiao, W., & Lu, D. (2015). A survey on wind turbine condition monitoring and fault diagnosis—Part I: Components and subsystems. *IEEE Transactions on Industrial Electronics*, *62*(10), 6536-6545.

Raj, A., Dwivedi, G., Sharma, A., de Sousa Jabbour, A. B. L., & Rajak, S. (2020). Barriers to the adoption of industry 4.0 technologies in the manufacturing sector: An inter-country comparative perspective. *International journal of production economics*, *224*, 107546.

Ren, Z., Verma, A. S., Li, Y., Teuwen, J. J., & Jiang, Z. (2021). Offshore wind turbine operations and maintenance: A state-of-the-art review. *Renewable and Sustainable Energy Reviews*, *144*, 110886.

renewablesnow. (2022). https://renewablesnow.com/news/europe-expected-to-add-42-gw-of-offshore-wind-in-2022-781698/

Rødseth, H., Eleftheriadis, R. J., Li, Z., & Li, J. (2020). Smart Maintenance in Asset Management–Application with Deep Learning. Advanced Manufacturing and Automation IX 9th,

Rødseth, H., Skarlo, T., & Schjølberg, P. (2015). Profit loss indicator: a novel maintenance indicator applied for integrated planning. *Advances in Manufacturing*, *3*, 139-150.

Rueter, G. (2021). How sustainable is wind power? https://www.dw.com/en/how-sustainable-is-wind-power/a-60268971

Sahnoun, M. h., Baudry, D., Mustafee, N., Louis, A., Smart, P. A., Godsiff, P., & Mazari, B. (2019). Modelling and simulation of operation and maintenance strategy for offshore wind farms based on multi-agent system. *Journal of Intelligent Manufacturing*, *30*, 2981-2997.

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.

Shafiee, M. (2015). Maintenance logistics organization for offshore wind energy: Current progress and future perspectives. *Renewable Energy*, *77*, 182-193.

Tchakoua, P., Wamkeue, R., Ouhrouche, M., Slaoui-Hasnaoui, F., Tameghe, T. A., & Ekemb, G. (2014). Wind turbine condition monitoring: State-of-the-art review, new trends, and future challenges. *Energies*, *7*(4), 2595-2630.

Tjøm, U. (2022). *Optimizing maintenance plans of offshore wind farms by calculating the likelihood of future turbine failures* The University of Bergen].

TWI. (2022). ADDRESSING THE CHALLENGES OF OFFSHORE WIND. https://www.twi-global.com/media-and-events/insights/addressing-the-challenges-of-offshore-wind

University, M. What is sustainability? https://www.mcgill.ca/sustainability/files/sustainability/what-is-sustainability.pdf

Wang, S., Wan, J., Li, D., & Zhang, C. (2016). Implementing smart factory of industrie 4.0: an outlook. *International journal of distributed sensor networks*, *12*(1), 3159805.

Xia, J., & Zou, G. (2023). Operation and maintenance optimization of offshore wind farms based on digital twin: A review. *Ocean Engineering*, *268*, 113322.

Zhang, T., Dwight, R., & El-Akruti, K. (2015). Condition based maintenance and operation of wind turbines. Engineering Asset Management-Systems, Professional Practices and Certification: Proceedings of the 8th World Congress on Engineering Asset Management (WCEAM 2013) & the 3rd International Conference on Utility Management & Safety (ICUMAS),

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