Test bench for Short Term Decision Support for Logistical operations of Offshore Wind farm

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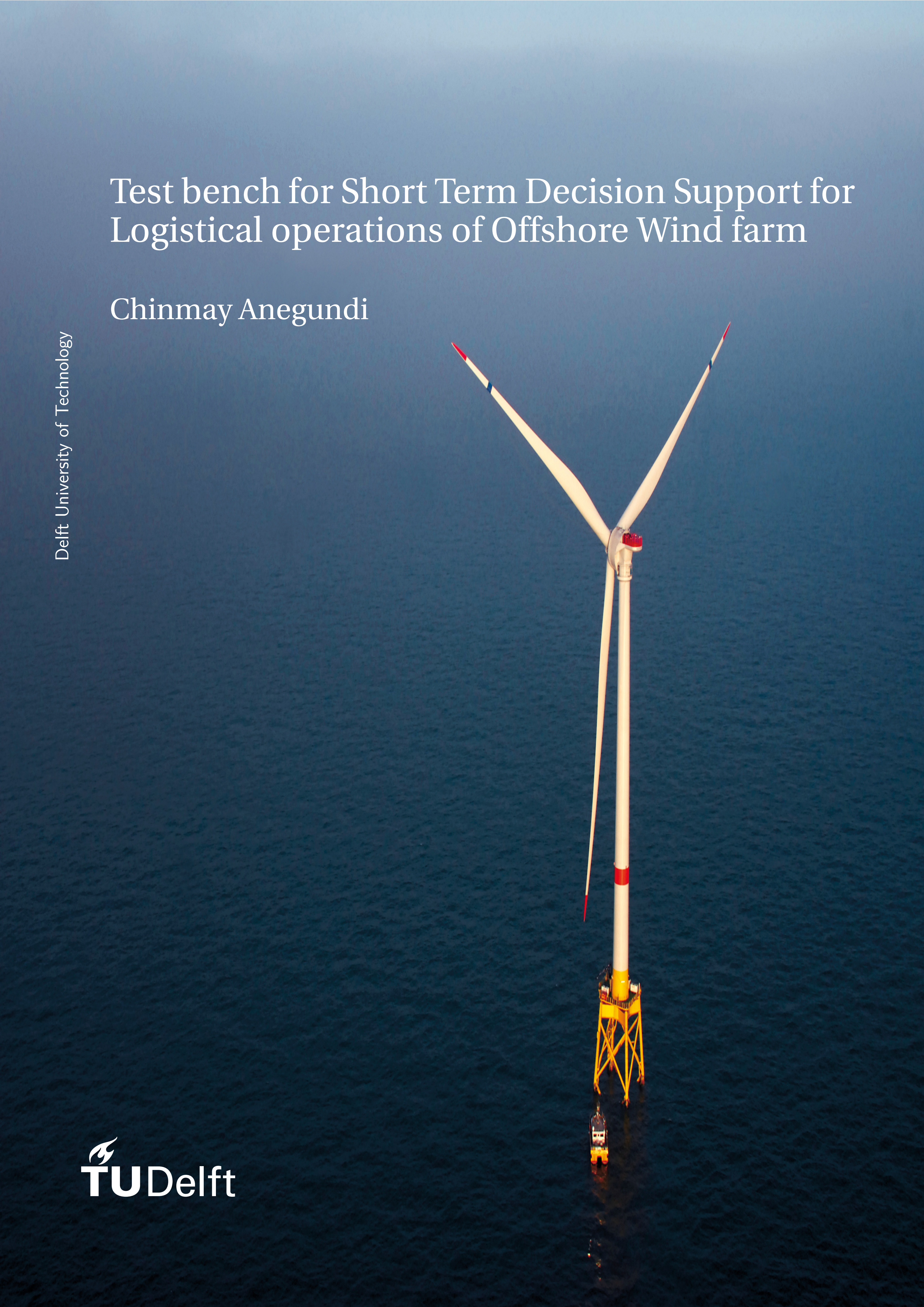

TEST BENCH FOR SHORT TERM DECISION SUPPORT FOR LOGISTICAL OPERATIONS OF OFFSHORE WIND FARM

by

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ABSTRACT

O&M contributes to about 25% of the total offshore wind farm costs which is rather large. It also influences the levelised production cost per kWh over the entire lifetime of the wind farm. Therefore, it is necessary to reduce the costs involved in O&M activities. One such activity is the logistics involved in O&M. The increasing logistical costs have been a challenge which can hamper the O&M market in the future. Therefore, it is important to take necessary steps to reduce the logistical costs. Wind farm operators have to take up logistical decisions to make optimal use of the available resources to maximise the wind farm availability. These decisions involve which turbines to repair, the route to follow considering constraints like weather conditions and vessel availability. A decision support tool aids in taking appropriate decisions to carry out the logistical activities. This calls for a testing tool which can assess the decisions taken by the planner or the decision support tool. Current research helps in developing a method to assess the quality of the decision taken by the decision maker or the decision support tool. This will help in making better decisions and reducing the costs involved in the logistics of O&M for OWF. The objective of this graduation project is to set up guidelines for a test bench to examine the optimality of the decisions taken by the planner or the decision tool to carry out the logistical operations for a shorter duration.

Chinmay Anegundi
Delft, April 2018

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NOMENCLATURE

Abbreviations

$ARMA$	Auto-Regressive Moving-Average
CM	Corrective Maintenance
$CO2$	Carbon Dioxide
$COP21$	21st Conference of Parties
CTV	Crew Transfer Vessel
ECN	Energy Research Centre of the Netherlands
EU	European Union
GHG	Greenhouse gases
$MTBF$	Mean Time Before Failure
$MTTF$	Mean Time to Failure
$MTTR$	Mean Time to Repair
$O\&M$	Operations and Maintenance
$OMCE$	Operations and Maintenance Cost Estimator
OWF	Offshore wind farm
PM	Preventive Maintenance
$RMSE$	Root-Mean-Square Error
$SCADA$	Supervisory control and data acquisition
SWH	Significant wave height
$VRPPD$	Vehicle Routing Problem with Pick-up and Delivery
WS	Wind speed
WT	Wind Turbine

Other Symbols

M	Markov transition matrix

P_{ij}	Probability of transition from state i to j
s	Number of states
U_{max}	Upper boundary layer of the wind speed state
U_{min}	Lower boundary layer of the wind speed state
V	Variance
$X(k)$	Wind speed forecast error in k-hour forecast
$Z(k)$	Random gaussian variable with mean zero and standard deviation σ_z
b	Distance between two points (in Haversine equation)
R	Radius of earth (6373 km)

Latin Symbols

α	Auto-regressive constant parameter
β	Auto-regressive constant parameter
σ	Standard deviation

1

INTRODUCTION, MOTIVATION AND OBJECTIVES

1.1. INTRODUCTION

The Earth's natural resources are being used extensively each year throughout the world. The dependence on the fossil fuels has resulted in the high emissions of greenhouse gases (GHGs) which have been one of the focal reasons for the increase in global temperatures. The GHG emissions have increased by 80% since 1970 [5]. In 2015, the 21st Conference of Parties (COP21) took place in Paris where 190 countries signed the universal agreement on climate to achieve the target of keeping the global warming below 2°C [6]. In order to keep the rising temperature below 2°C by the end of 21st century, the maximum allowable carbon dioxide (CO2) emissions are 2900 Gt. Out of this 1900 Gt has already been spent. So to avoid the irreparable damage from happening, the emissions have to be controlled in the coming future. The remaining fossil fuel reserves can add up to the existing CO2 emissions, therefore it is very important to move towards the renewable energy sources. The 2020 renewable energy targets for EU which sets a binding target of 20% of the total energy consumption to be produced by renewables by the year 2020 has made the EU countries to commit to their individual national renewable goals [7]. Figure 1.1 shows the individual national renewable energy goals of EU members and their position by 2014.

1.2. OFFSHORE WIND ENERGY

Wind energy is one of the most notable renewable energy sources and shares a large part of the global energy market. The global wind energy capacity has been increasing steadily over the years and by June 2017, the total installed global wind capacity was 511 GW as seen in figure 1.2 [1]. A vast majority of wind energy is being generated by onshore wind farms. Onshore wind farm developers are faced with many challenges such as lack of area on land, increasing population, noise issues and social acceptance. These issues make it very complicated to acquire land for the new wind farms. On the other hand, better wind conditions and an abundance of space has compelled the wind farms to move offshore. Offshore wind turbines are less obtrusive than turbines on land, as their apparent size and noise can be mitigated by distance. Due to the lower surface roughness on water than land, the average wind speed is considerably higher over open water. Capacity

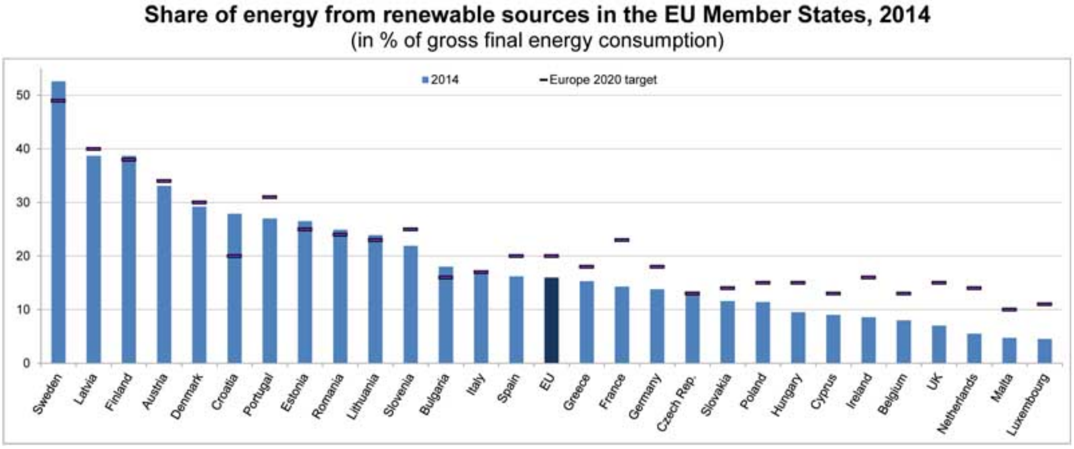


Figure 1.1: Share of energy from renewable sources in the EU member states, 2014

factors are considerably higher than for onshore and near-shore locations which allow offshore turbines to use shorter towers, making them less visible and cheaper, although the submerged structure and foundation are expensive. In addition, installing wind turbines offshore has several advantages. Onshore wind farms are faced with the challenges in transporting large components which can be easily transported offshore using various marine shipping and handling and lifting equipments, which far exceeds the lifting requirements for multi-megawatt wind turbines [8].

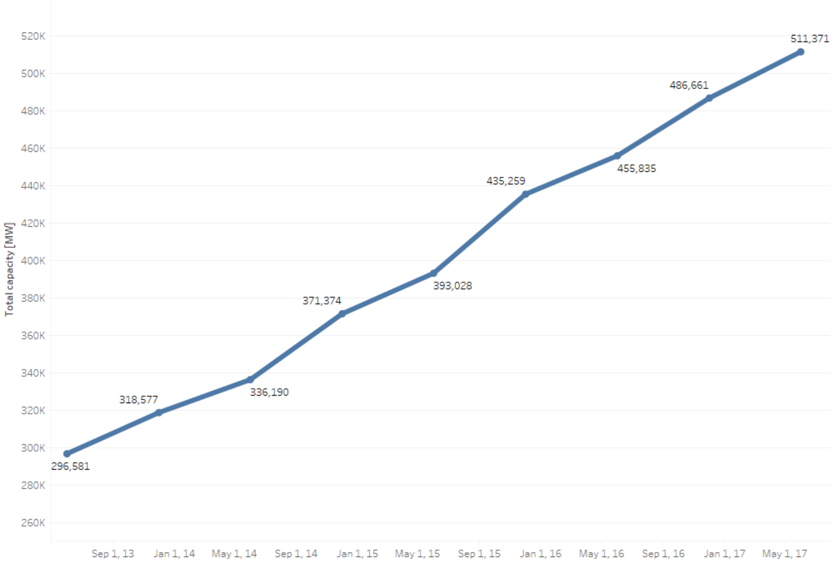
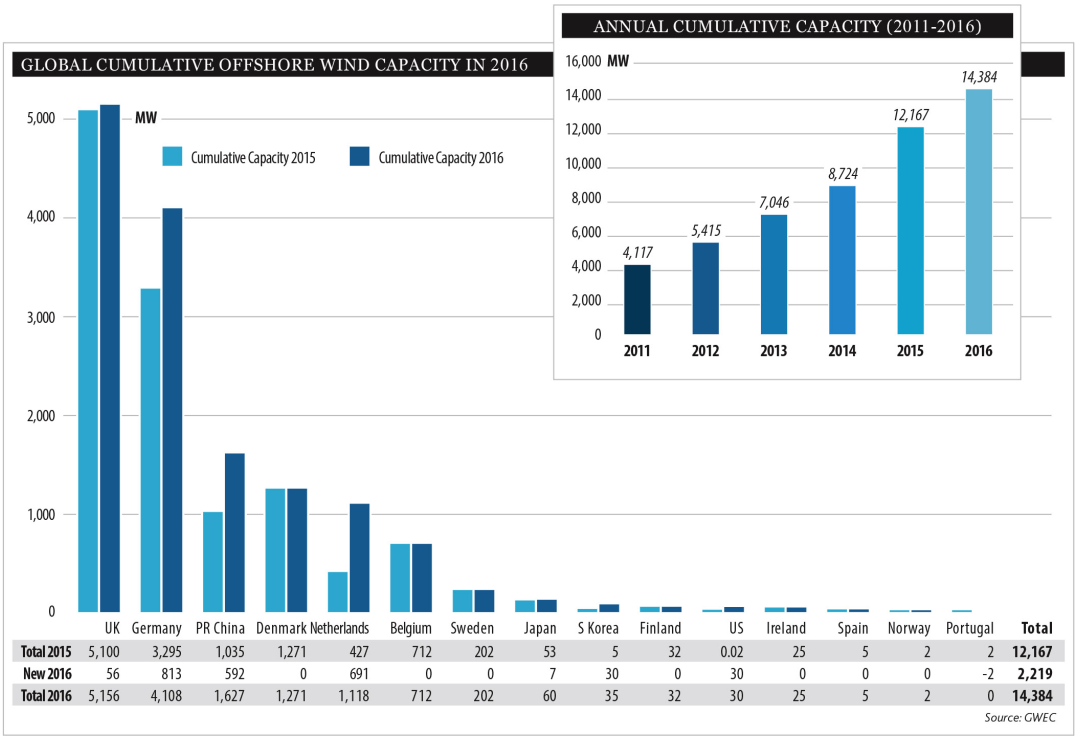


Figure 1.2: Global installed wind capacity [1]

Such an offshore wind farm is situated in the sea far from the coast and consists of a number of wind turbines arranged in an optimal configuration to extract maximum energy possible. As of mid-2016, Europe has 3,344 offshore wind turbines with a combined capacity of 11,538 MW fully grid connected. These turbines are a part of 82 wind farms across 11 countries in the European waters [9]. Similarly, China, by the end of 2015, had a cumulative installed capacity of more than 1 GW. Countries like US and India have started work on their offshore wind energy plans and are likely to commence the energy production within a few years [10].



	UK	Germany	PR China	Denmark	Netherlands	Belgium	Sweden	Japan	S Korea	Finland	US	Ireland	Spain	Norway	Portugal	Total
Total 2015	5,100	3,295	1,035	1,271	427	712	202	53	5	32	0.02	25	5	2	2	**12,167**
New 2016	56	813	592	0	691	0	0	7	30	0	30	0	0	0	-2	**2,219**
Total 2016	5,156	4,108	1,627	1,271	1,118	712	202	60	35	32	30	25	5	2	0	**14,384**

Source: GWEC

Figure 1.3: Global offshore wind capacity, 2016

The increased need for renewable energy has also shifted the focus on the offshore wind energy. Wind energy is expected to be able to supply a considerable percentage of the future energy demands. Offshore wind energy is still not commercially viable. Even with the intervention of the government and its subsidies, the profit margin is still small. This shows the exorbitant costs involved in the development and maintenance of offshore wind farms. By the end of 2015, the global offshore wind industry increased its capacity by 3.4GW, bringing it to a total of 12GW [10].

Offshore wind farms are constantly faced with challenges which have to be overcome in order for the proper functioning of the turbines. Challenges like loads due to wind and waves, water depth, soil conditions, weather conditions are some of the things to be considered during the design phase.

1.3. OFFSHORE OPERATIONS AND MAINTENANCE

Wind power industry has had a stable growth in the past few years due to major developments in offshore wind technologies.

All systems and components in the wind farms need to be maintained. The turbines are usually visited twice a year with 3 to 5 days duration of preventive maintenance. Along with the preventive maintenance, corrective maintenance is also carried out when a component fails and has to be fixed for a proper functioning of the wind turbine [11]. It is expected that with the improvements in reliability and maintenance, the frequency of the preventive maintenance can be reduced.

The contribution of the operations and maintenance costs to the offshore wind farm costs is rather large. Sometimes it can go up to 25-30 percent of the total levelized production cost per kWh over the entire lifetime of the turbine [12]. This is rather high compared to the costs involved in the onshore wind farms. The O&M costs of offshore wind farms is EUR 0.03 per kilowatt hour of electricity. Therefore, it is necessary to bring down these costs as much as possible. According to Glen Donnelley, “These costs can be reduced by one-third of the existing costs within a span of ten years” [13]. To achieve this, various strategies are adopted which incorporate various techniques to bring down the O&M costs.

Figure 1.4: Examples of different offshore access systems; clockwise: Windcat workboat, Fob Lady, SWATH and helicopter .

One of the most relevant maintenance aspects for offshore wind farms is the transportation and access vessels. Nowadays, offshore wind farms make use of small boats like the Windcat, Fob Lady or SWATH boats to transfer personnel from ports to the turbines. In times of bad weather conditions, helicopters are also used. Figure 1.4 shows the different types of access systems. Differently sized transportation systems are used depending on the size of the equipment to be transported. For example, larger boats are used to transport components like yaw drive, main bearing, etc. Various new offshore access systems are being developed to assist the personnel even in the harsh weathers. One such system is Amplemann which uses hydraulics to stabilise the gangway so that the personnel can be easily transferred between the boat and the turbine [14].

1.4. DECISION SUPPORT TOOLS

Matthias Hofmann [9] gives an overview of the existing quantitative models for decision support that calculate the costs and income of an offshore wind farm over its lifetime.This resulted in various models developed for various purposes from estimating total project costs to management tools. Many of the above-mentioned tools focused on the operations and maintenance aspect. TU Delft and ECN have a broad continuum of advanced models such as CONTOFAX, RECOFF and the ECN O&M tool and OMCE model are state-of-the-art O&M cost estimation tools.

Two of the existing short-term decision support models are discussed here. One of these two tools is the ECN's Operations and Maintenance Cost Estimator (OMCE) tool and the other tool is from the University of Strathclyde. These two tools were studied as they describe the logistical aspect of O&M. The above-mentioned tools are used to carry out the day to day vessel routing strategies and also to monitor, control and optimize the O&M processes.

In 2004, ECN partnered with the We@Sea consortium to develop a tool to estimate the future O&M costs. OMCE calculator developed by ECN [11] supports the process of monitoring, control and optimization of the O&M data. The OMCE tool is meant to be used during the operational period to assess the O&M effort to be required in the future period.

The objective of the logistic aspect includes the generation of information for repairs and maintenance to be used during the logistical actions and the generation of information such as accessibility, repair time, etc. to be used as inputs in OMCE calculator.

A model was developed at the University of Strathclyde, Glasgow [15] which allows an effective planning of resources by automating the process of logistical decision making of maintenance actions for OWF. This tool recommends a day-to-day vessel routing strategy which will assist in minimizing costs and to maximize the number of turbines repaired. The paper takes into account a case study to demonstrate the tool's capabilities.

The shortest route to take to repair all the turbines is determined by the logical algorithm which is used to determine the drop-off and pick-up order. This logic then is used to estimate the time taken to carry out the repairs.

1.5. RESEARCH MOTIVATION

As seen in section 1.2, the last decade has seen a considerable growth in offshore wind power capacity and the amount of electricity produced is increasing every year. Despite the significant growth in the offshore wind energy capacity, the availability of the WTs is greatly limited due to the harsh marine environment and the rapidly changing weather conditions. The field data analysis from the SCADA system shows that the availability for onshore wind farms is higher than that for offshore wind farms [16].

Currently, the O&M costs constitute a considerable portion of the total costs involved in an OWF project. O&M costs for a typical OWF with 20-year life accounts for about 25%-30% of the lifetime power generation cost [17]. O&M of offshore wind farms is more difficult and expensive than the equivalent activities for onshore wind farms [12]. Therefore, in order to make offshore wind energy cost-competitive with other renewable energy sources, these costs have to be reduced considerably.

Logistics management of maintenance is critical in offshore wind energy industry. When the alert is detected in the monitoring system, a maintenance plan is scheduled for the faulty equipment. Necessary transportation means, service vessels, qualified maintenance technicians are allocated to perform the repair tasks. Any failure to accomplish the required task due to circumstances such as unavailability of vessels or staffing problems may adversely affect the wind farm availability and thereby be affecting the power output as well as profitability. Therefore, a well-organised logistics management is required not only to reduce the O&M costs but also to ensure that the power generation matches the demand [18].

The effectiveness of the planning depends on the decision taken in the planning phase. The outcome is influenced by uncertainties, particularly the weather or accessibility. Decision makers take the support of the tools to make their logistic decisions. At the moment it is not known which decisions (conservative or optimistic) or which decision support tools are best and a tool is necessary to test this. The current research effort will help in testing the effectiveness of the various decisions taken by the decision maker in terms of logistical planning for O&M of OWF.

1.6. OBJECTIVE

The objective of this project is to test the effectiveness of the decisions from a decision maker. This test bench is for the decision makers or for decision strategies rather than an extension for the existing decision support tools.

The user generally has to deal with what kind of information is available and what to give back in terms of the schedule and with this test bench the user can be forced to comply with the restricted information given regarding the weather predictions, wind farm status and the vessel and crew data. A reasonable insight and answers to the questions regarding the information of the farm are needed so that the decision maker can present a decision or a schedule. The details of the inputs and the outputs will be different from the tool but the fundamentals will be very similar. Eventually, the goal is to be able to test the decision support tools, but due to the complexity involved in the decision support tools, the decisions of a decision maker is used.

The tool is simpler and stricter as the user needs to use the inputs provided by the tool which have precise specifications.

1.7. REPORT OUTLINE

Chapter 1 gives a brief introduction to the offshore wind energy industry and its operations and Maintenance. A brief discussion of the existing decision support tools which were used as an inspiration for this thesis. Next, the main motivation to carry out this study and objectives which had to be achieved to complete this study have been mentioned.

Chapter 2 shows the overview of the test-bench developed along with its major elements involved. The overview of the test-bench functions and its characteristics along with the assumptions considered in this thesis are mentioned.

Chapter 3 describes how the test-bench was developed and the methods used to develop different aspects of this test-bench.

Chapter 4 presents the case studies performed in the project along with its results and discussions.

Finally, chapter 5 includes the conclusion of the thesis work along with the recommendations for future work.

2

TEST-BENCH DESIGN AND ITS CHARACTERISTICS

2.1. DESCRIPTION

As seen from section 1.6, the objective of this study is to test the effectiveness of the decisions taken by the decision maker and to achieve this, a test bench is developed. The test-bench provides the the decision maker with weather forecast and the status of the failed turbines in the wind farm for a short-term based on the scenario set up by the moderator for which the planning strategy regarding the quality of the weather forecast, number of failed turbines, the fleet size and composition is tested. Based on these, the decision maker plans the maintenance strategy for the upcoming shift using certain input to the test bench which which simulates the planning with the real weather. The moderator is the person who sets up the conditions and constraints within which the test bench can operate. The moderator can vary and change various parameters for the test bench which serve as the working conditions for the decision maker whose decisions are restricted to these boundary conditions. The decision maker or the user is a person who makes decisions to carry out the logistics operations for the O&M activities. It can be seen from the flowchart in figure 2.1, how the inputs for the decisions are based on the moderator inputs. Based on the outcomes of this test bench, it can be analysed if the status of the maintenance activity matches the initial planning.

2.2. OVERVIEW OF THE TOOL

The tool developed is a simplified version of what a future test bench would look like.

The flowchart in fig. 2.1 shows the inputs and the outputs which the moderator and the decision maker enters and receives as outputs. The test bench tool was developed in MATLAB.

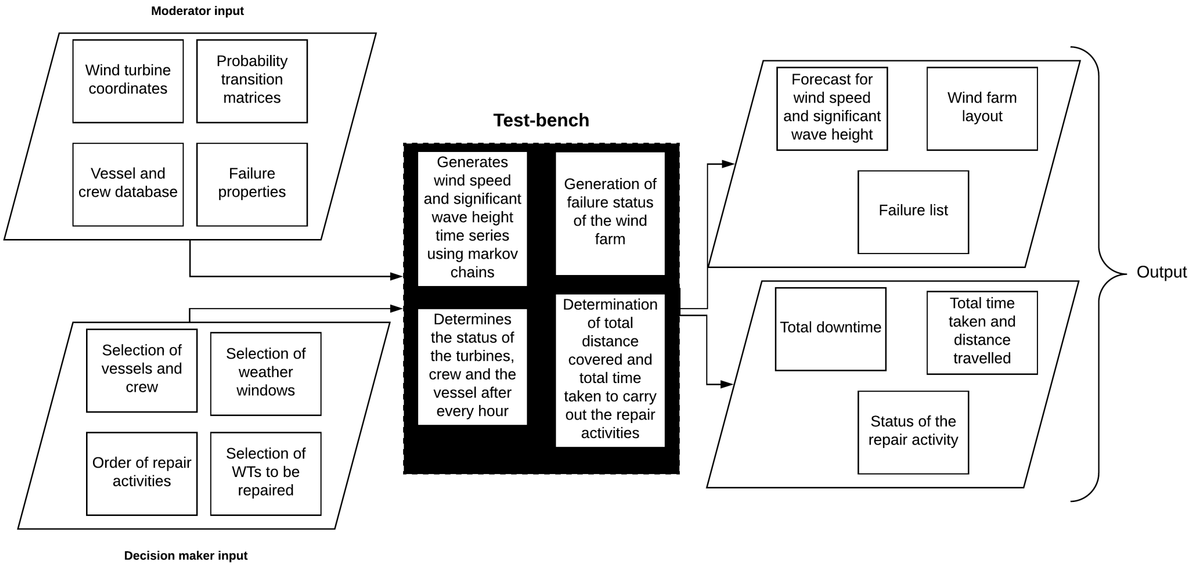


Figure 2.1: Flowchart for the test bench

2.2.1. MODERATOR INPUTS AND OUTPUTS

The test bench requires two sets of inputs for the O&M planning. The flowchart in fig. 2.1 clearly distinguishes between the moderator inputs and the decision maker inputs. As said before, the moderator sets up the conditions and based on this, the decision maker makes the planning.
The inputs from the moderator are explained below.

1. *Transition probability matrices*: This matrix is used to generate a stochastic forecast of the wind speed and significant wave height over a certain period determined by the user. This matrix contains the probabilities of the transition from one state to the other.

2. *Failure properties*: The failure properties involve the classification of different types of failure that occur in an offshore wind turbine. This input also involves the failure rates of each of those categories which can be seen in the later sections.

3. *Wind turbine coordinates*: This involves the global coordinates of all the turbines involved along with the coordinates of the onshore or offshore base.

4. *Vessel and crew database*: The database gives the details of the fleet in consideration. The database can be modified according to the needs of the user. The database requires inputs for certain parameters to perform necessary analysis such as types of vessels along with their speeds, capacity and their WS and wave height restrictions. Information such as the number of personnel that can be allowed on to the vessels needs to be mentioned as well. Similarly, the crew database requires certain inputs as well, such as a number of available technicians for that particular day and their working shift hours

The outputs from these inputs serve as the boundary conditions within which the decision maker has to operate and make decisions. These include,

1. *Forecasts for wind speed and significant wave height*: These forecasts are obtained by using the probability transition matrices and the forecast errors generated. These provide the decision maker with the weather forecast for a certain number of hours from which the weather windows can be deduced.

2. *Wind farm layout*: The coordinates of the WTs in the OWF helps in providing the decision maker with the OWF layout as a visual aid which can be used in the planning procedure.

3. *Failure list*: Based on the failure list and its classification, a failure list is generated which shows the failed WTs.

2.2.2. DECISION MAKER INPUTS

The outputs from the previous section serve as a basis for the inputs from the decision maker.

1. *Selection of weather windows*: Based on the forecasts observed from section 2.2.1, the decision maker can choose the workable time when the OWF is accessible for the vessels. Along with this, the decision maker also has the option to choose the starting time for the O&M activities.

2. *Selection of WTs to be repaired*: The failure list provides a list of failed WTs along with their failure categories and the ideal time required to repair them. Based on this data, the decision maker can decide on which turbines to be visited by the technicians to be repaired.

3. *Selection of vessels and crew*: The next set of inputs involve the selection of vessels and number of crews which can be selected based on the vessel and crew database available which is set up by the moderator.

4. *Order of repair activities*: This part involves the instructions entered by the decision maker to the vessels following a certain order in which the failed WTs are to be visited.

2.2.3. TEST BENCH OPERATIONS

The test bench performs certain operations and these depend on the source of the inputs(moderator or the decision maker). Overall, there are four major processes that take place on the test bench.

1. Generation of wind speed and significant wave height time series

2. Generation of failure status of the OWF

3. Calculation of the distances travelled and the time taken to carry out the repair activities:

4. Determination of the status of the turbines, crew and the vessel after every hour

2.2.4. OUTPUTS FROM THE TEST BENCH

Based on the inputs from the decision maker, the final outputs obtained from the test-bench are.

1. *Total downtime*: The WTs are selected and repaired based on the planning devised by the decision maker and at the end of the planning period, the downtime of the turbines repaired is calculated and displayed.

2. *Total time taken and distances travelled*: This output provides the total time taken by the vessels and the crew at every step of the operation and the distance travelled by the vessels at every stage is calculated based on the coordinates of the WTs and the operation based as set up by the moderator.

3. *Status of the repair activity*: After all the inputs, the status of all the elements involved are presented together. This includes the status of the vessels at every time step along with the position of the crew and the status of the turbines being repaired.

These outputs help in achieving the objectives of testing the effectiveness of the decisions made by the decision maker. The following chapter discusses the methods and processes used to carry out the test bench operations.

2.2.5. ASSUMPTIONS

The development of this test bench consisted of several assumptions, such as

1. The wind speed data and significant wave height data are not correlated.

2. The starting and the ending point of the vessels is the onshore/offshore base.

3. Only one crew is assigned per failed turbine.

4. While repairs in the nacelle, the ascent time is considered in the repair time.

5. The crews are assigned to the vessels and shall not be changed during the operations.

3

Methodology

3.1. Generation of weather forecasts

The OWF accessibility has a major impact on the O&M planning. Constraints on met-ocean conditions are used. These met-ocean conditions consist of significant wave height and wind speed. Forecasting of these conditions is crucial for the O&M planning and for this, stochastic inputs of wind speed and significant wave height are required. A representative time series need to be generated which can be done using the Markov chains. The generated wind series have to be realistic in order to achieve realistic results and their auto-correlation needs to be credible. Markov chains can be used to do this. This approach can be used to generate wind speeds and significant wave heights. A Markov chain models a stochastic process in which a state changes with discrete time steps. In a Markov chain, it is assumed that the probability of a certain state depends on the past states. It is a probabilistic forecasting method. Apart from just estimating the point forecasts it also estimates the probability distribution associated with it. This approach is relevant for time series with any probability distribution. The application of Markov chains requires the breaking down of the amplitude range into several discrete states. The number of equidistant amplitude intervals for the states acts as a calibration parameter for the Markov chains [19].

The order of the Markov chains is also one of the important parameters. It gives the number of past states that influence the probability of the present state. The first order Markov chain involves the dependence of only the previous state over the present state. The low order chains are preferable for two reasons. The number of parameters to be estimated is kept to be a minimum, so that better estimates are obtained. Second, the subsequent use of the fitted model to calculate other quantities, such as the probabilities of long windows of good and workable weather, is simpler.

The measured wind speed data set is divided into a number of states, s. The number of states, s is subjective. There will be s X s transitions between the two successive time instances. [20]

A Markov transition matrix, M is generated with size s X s.

$$M = \begin{pmatrix} P_{11} & \dots & P_{1n} \\ \vdots & \vdots & \vdots \\ P_{n1} & \dots & P_{nn} \end{pmatrix} \tag{3.1}$$

The element P_{ij} of the matrix M represent the number of times transition from state i to j has taken place. The matrix is then converted to a probability transition matrix M where P_{ij} is defined as

$$P_{ij} = \frac{m_{ij}}{\sum_{j}^{i,j=1...s} m_{ij}} \tag{3.2}$$

As described earlier, the generation of wind series is achieved using Markov chains. For this, a dataset used by Lotte Engelen [21] is considered. The wind speeds in the dataset are divided into a number of states s. The choice of s is subjective but here we have considered s=10. The divided wind speeds per state are shown in the following table 3.1.

Table 3.1: Overview of wind speeds per state used in this research.

State	Wind Speed (m/s)		State	Wind Speed (m/s)
1	0-2		6	10-12
2	2-4		7	12-14
3	4-6		8	14-16
4	6-8		9	16-18
5	8-10		10	18-20 (=max)

The probability transition matrix generated using equation 3.2 is shown below in table 3.2. Its size is determined by the number of states the data is divided into. Here, we have considered 10 states and therefore, the size of the matrix is 10x10. Here, i refers to the rows and j refers to the columns.

Table 3.2: Probability transition matrix for wind speed

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
1	0.596	0.371	0.026	0.007	0	0	0	0	0	0
2	0.075	0.705	0.161	0.051	0.004	0.004	0	0	0	0
3	0.008	0.241	0.434	0.297	0.015	0.004	0.001	0	0	0
4	0.001	0.031	0.12	0.683	0.132	0.031	0.001	0.001	0	0
5	0	0.005	0.012	0.256	0.465	0.249	0.01	0.003	0	0
6	0	0.003	0.002	-0.001	0.196	0.67	0.107	0.022	0	0.001
7	0	0	0.002	0.003	0.015	0.252	0.52	0.199	0.007	0.002
8	0	0	0	0.002	0.004	0.042	0.166	0.668	0.098	0.02
9	0	0	0	0	0	0.002	0.018	0.301	0.425	0.254
10	0	0	0	0	0	0.002	0.003	0.032	0.128	0.835

Using the table 3.2, wind series can be generated by applying the following process:

- A cumulative transition probability matrix is generated from P meaning that the final value of each row is 1.
- On obtaining the cumulative transition probability matrix, an initial state i is chosen randomly.

- A random number between 0 and 1 is chosen and is compared to the values in row i of the cumulative transition probability matrix. The state with the value closest to the uniform random number gives the state j.
- Another uniform number, ϵ between 0 and 1 is chosen. This is used to convert the wind speed state to an actual wind speed. It is achieved using the following equation,

$$U = U_{min} + \epsilon(U_{max} - U_{min}) \tag{3.3}$$

Here U_{min} and U_{max} are the lower and upper boundary layers of the wind speed state j.

The significant wave height time series can be generated using the same approach. The probability transition matrix for significant wave height (table 3.4) can be generated using a dataset and dividing them into states as shown in table 3.3.

Table 3.3: Overview of significant wave heights per state used in this research

State	**Significant wave height (m)**	**State**	**Significant wave height (m)**
1	0 - 0.5	**11**	5.0 - 5.5
2	0.5 - 1.0	**12**	5.5 - 6.0
3	1.0 - 1.5	**13**	6.0 - 6.5
4	1.5 - 2.0	**14**	6.5 - 7.0
5	2.0 - 2.5	**15**	7.0 - 7.5
6	2.5 - 3.0	**16**	7.5 - 8.0
7	3.0 - 3.5	**17**	8.0 - 8.5
8	3.5 - 4.0	**18**	8.5 - 9.0
9	4.0 - 4.5	**19**	9.0 - 9.5
10	4.5 - 5.0	**20**	9.5 - 10.0

Table 3.4: Probability transition matrix for significant wave height

States	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0.146	0.683	0.151	0.012	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0.156	0.581	0.221	0.026	0.013	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0.018	0.290	0.346	0.309	0.018	0	0	0.018	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0.636	0.255	0.418	0.236	0.036	0.018	0	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0.070	0.175	0.386	0.193	0.123	0.018	0.0175	0.018	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0.050	0.100	0.3	0.200	0.200	0.150	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0.019	0.056	0.259	0.296	0.130	0.204	0.037	0	0	0	0	0	0	0	0
10	0	0	0.025	0	0	0	0.025	0.15	0.175	0.2	0.15	0.225	0.025	0.025	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0.077	0.154	0.282	0.256	0.154	0.051	0.026	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0.032	0.097	0.226	0.196	0.196	0.161	0.032	0.032	0	0.032	0	0	0
13	0	0	0	0	0	0	0	0	0	0	0.167	0.167	0.167	0.222	0.111	0.056	0	0	0	0
14	0	0	0	0	0	0	0	0	0	0	0	0.154	0.231	0.077	0.308	0.154	0	0	0	0
15	0	0	0	0	0	0	0	0	0	0	0.083	0.083	0.167	0.167	0.083	0.25	0.083	0.083	0	0
16	0	0	0	0	0	0	0	0	0	0.125	0.125	0.125	0.125	0.125	0.375	0	0	0	0	0
17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.25	0.25	0.25	0	0	0.25
18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.2	0	0	0.4	0.2
19	0	0	0	0	0.333	0	0	0	0	0	0	0	0	0.3333	0	0	0	0	0	0.333
20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.333	0.667	0	0

An example of the generated wind speed and significant wave height time-series for 168 hours can be seen in figure 3.1. These are generated using the procedure mentioned in section 3.1 and the probability transition matrices under consideration.

Note: The wind speed and significant wave height in the real-life conditions are correlated and the wave height depends on the surface roughness, fetch length and the wind speed. However, for the simplicity of this study, the correlation between the wind speed and significant wave height is not considered.

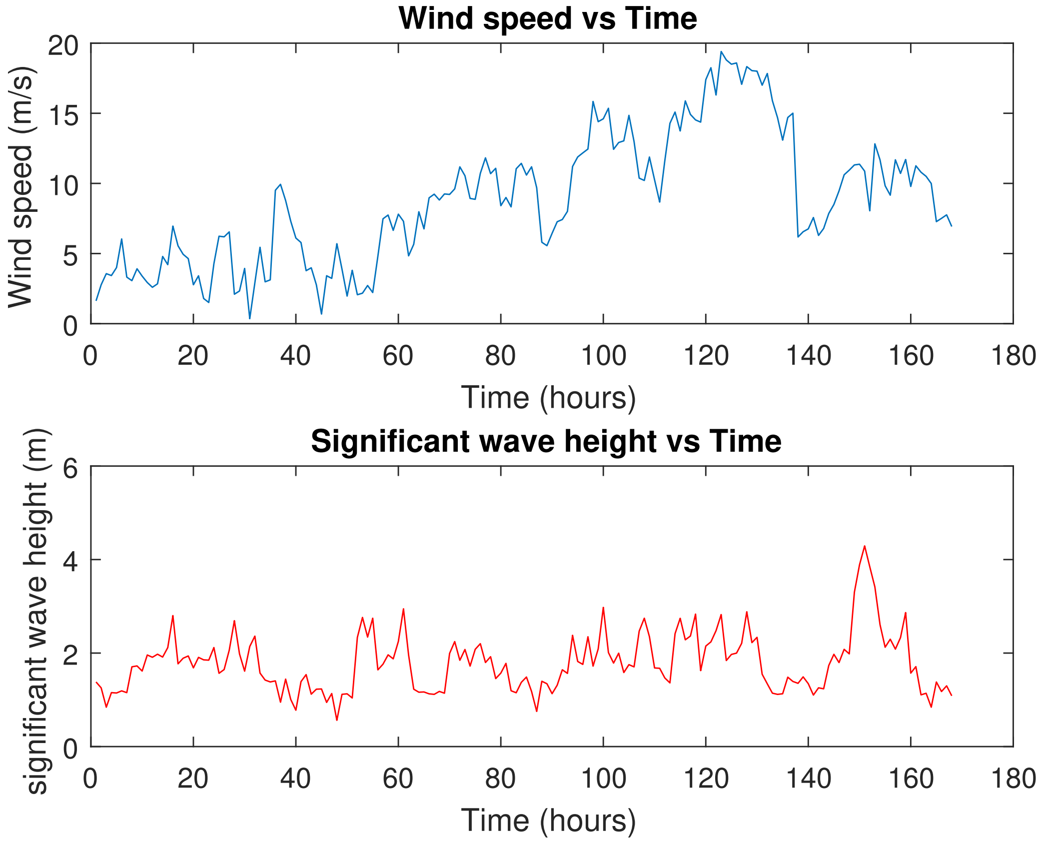


Figure 3.1: Real Wind speed and Significant wave height vs time

3.1.1. FORECAST ERRORS

The increase in the amount of wind power production requires a possible outcome of total wind power in the daily operation planning of the power system. The first step for a proper planning is the wind speed forecasts. L. Soder [22] provides a method that stimulates the possible outcomes of the wind speed forecasts based on stochastic optimisation to be used for operational planning. The method involves simulation of wind speed forecast errors which can then be added to the real time wind series to get possible outcomes for wind speeds forecasts.

Wind speed forecast errors are simply a sequence of observations, each recorded at a specific instant of time. A *discrete* time series is one in which the observations are recorded at discrete points in time with a constant time interval between the points and in this thesis, the wind speed forecast errors considered are discreet. Since the time series is composed of observations from a single location at a time, it can be described as *uni-variate*.

A common model used to simulate discrete and uni-variate time series is the Auto-Regressive Moving-Average (ARMA) model. An autoregressive model is a representation of a type of random process, it is used to describe certain time-varying processes in nature, economics, etc. The autoregressive model specifies that the output variable depends linearly on its own previous values. Moving-average model is used to model univariate time series and it specifies that the output variable linearly depends on the current and various past values of a stochastic term. The ARMA is considered to be an ideal model, which means that for certain time series there is only one set of parameters to describe the time series. It is also linear, so it requires much less computation to find these parameters than non-linear models require. The model assumes the time series to be invertible, where the present observations are decreasingly dependent on the past observations as one moves further back in time. This is inherently true for wind speed forecast errors since they are dependent on the ability to predict wind speeds. Wind speed forecast error time series can be verified as invertible if the autocorrelation of the time series decreases with increasing time difference.

In [22] it is assumed that the wind speed forecasts are available for a particular site. The focus is then to imitate realistic possible outcomes, which have the stochastic behaviour regarding the forecast errors and correlation between different forecast errors.

Wind speeds forecast errors at a certain site are simulated using the Auto-Regressive Moving Averages series. This is defined as

$$X(0) = 0 \tag{3.4}$$

$$Z(0) = 0 \tag{3.5}$$

$$X(k) = \alpha X(k-1) + Z(k) + \beta Z(k-1) \tag{3.6}$$

where
X(k)= wind speed forecast error in k-hour forecast
Z(k)=random Gaussian variable with standard deviation σ_z and mean zero
α and β are constant parameters

In this study, ARMA(1,1) model is used which means that the model uses the autoregressive model of order 1 and moving-average model of order 1. The order of an autoregression and a moving average is the number of immediately preceding values in the series that are used to predict the value at the present time, which, in this case, is 1 [23]. A unique set of three parameters α, β and σ_z describe an ARMA (1,1) time series. The Auto-Regressive parameter α determines to which degree the previous value in the time-series influences the current value. The Moving-Average parameter β determines to what degree the random Gaussian variable of the previous parameter in the time-series influences the current value.

An illustration of how the ARMA(1,1) model simulates the wind speed forecast errors is shown. Realistic values for parameters α, β and σ_z are considered and then used to create the ARMA(1,1) time series. L. Soder [22] considered α=0.95, $\beta = 0.02$ and σ_z=0.5 and using these parameters three possible ARMA(1,1) time series are obtained as shown below in figure 3.2.

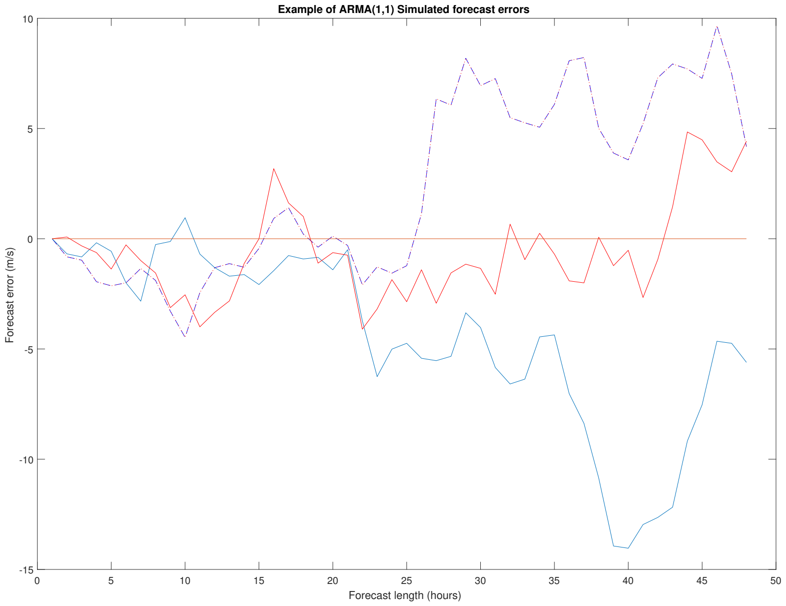


Figure 3.2: Three possible ARMA(1,1) wind speed forecast error time series using the parameters α = 0.95, β = 0.02, and σ_z=0.5.

The wind speed forecast errors generated using the above series are then added to the wind speed signal generated by Markov chains to obtain the wind speed forecast $W_f(k)$.

$$W_f(k) = W(k) + X(k) \tag{3.7}$$

The Root Mean Square Errors (RMSE) at every forecast length should have the same standard deviation as values of the time series at each forecast length. The standard deviation of the forecast error can be calculated by solving for the variance as follows

$$V(0) = 0 \tag{3.8}$$

$$V(1) = \sigma_z^2 \tag{3.9}$$

$$V(k) = \alpha^2 V(k-1) + (1+\beta^2 + 2\alpha\beta)\sigma_z^2 \tag{3.10}$$

If $k \geq 2$, equation 3.10 can be rewritten as

$$V(k) = \sigma_z^2(\alpha^{2(k-1)} + (1+1+\beta^2+2\alpha\beta)\sum_{i=1}^{k,1}\alpha^{(i-1)}) \tag{3.11}$$

The standard deviation of the forecast error can simply be calculated as

$$\sigma(X(k)) = \sqrt{V(k)} \tag{3.12}$$

The parameters $\alpha, \beta and \sigma_z$ can be optimized to get the best match with the measurements as

$$min Q(\alpha, \beta, \sigma_z) \tag{3.13}$$

where

$$Q(\alpha,\beta,\sigma_z) = \sum_{k=1}^{K} [RMSE_{measured}(k) - RMSE_{ARMA}(k)]^2 \tag{3.14}$$

$RMSE_{measured}(k)$=measured RMSE data for k-hour forecast
$RMSE_{ARMA}(k)$=calculated ARMA RMSE value for k-hour forecast.
K=number of forecast errors used for optimisation.

This process is adopted for forecasting significant wave heights as well and the resulting forecasts for wind speed and significant wave height can be seen in figure 3.3

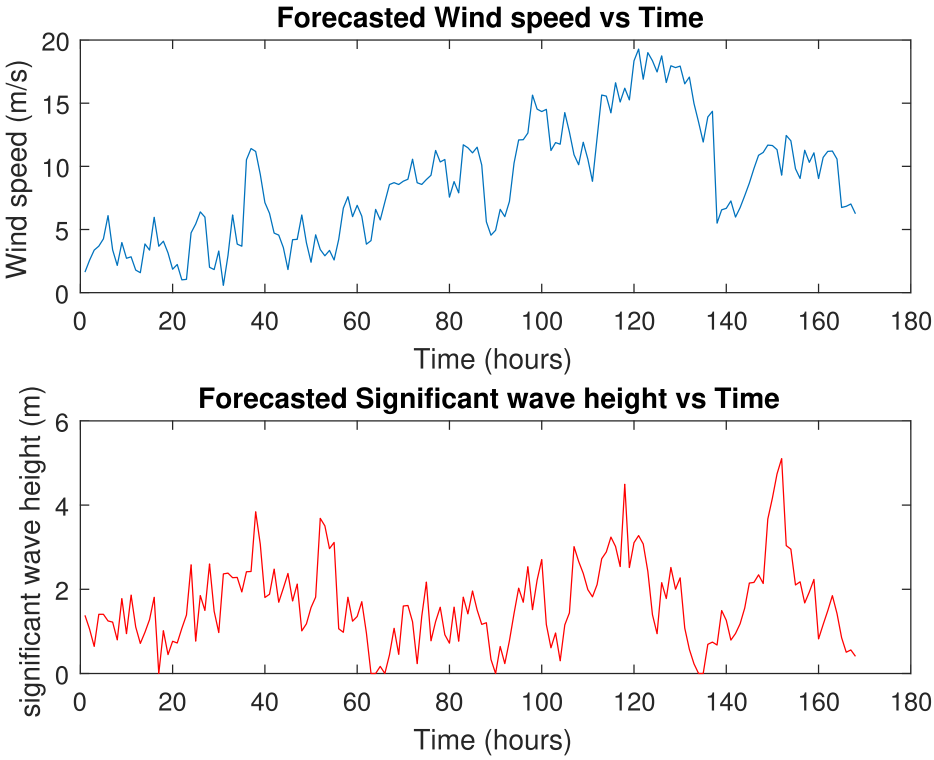


Figure 3.3: Forecast for wind speed and significant wave height vs time

3.2. MAINTENANCE ACTIVITIES

Maintenance accounts for by far the largest portion of O&M effort, cost and risk. The maintenance activity is the upkeep and repair of the physical plant and systems. It can be divided into preventative maintenance and corrective maintenance.

- *Preventive Maintenance*
  This refers to the type of maintenance activities that are scheduled in accordance with the wind turbine's manual, designed by the manufacturer. This type of maintenance activity is planned with respect to the elapsed time since the previous maintenance [24]. Preventive maintenance covers annual service maintenance and condition-based maintenance. It is assumed that PM activities consist of short duration and

may be carried out in several work shifts. During PM, the turbine is stopped for the duration only for maintenance work [25].

- *Corrective Maintenance*
  This refers to the maintenance activity carried out after a fault recognition or failure of any component has occurred to return it to the state to perform its required function [26]. If a failure occurs, the turbine stops working until it has been repaired. Because of this possibility and the limited accessibility to the offshore wind farms, this occurrence of unexpected failures can have a severe impact on the availability of the turbine and the overall power production of the farm. Failures are classified into major and minor failures according to the logistic needs for the repair. Minor failures on wind turbines require workboats or helicopters whereas the major failures always require a workboat. This classification is necessary due to the significant difference in dimension and weight of equipment and spare parts required for the maintenance. Each repair action is assumed to require on maintenance team [25].

3.3. VESSEL AND CREW DATABASE

The choice of vessel fleet composition will have a great impact on the O&M costs for the offshore wind farm. Weather conditions at the site of the wind farm, distance to the onshore/offshore base and the type of maintenance activity required governs the fleet composition.

Preventive and corrective maintenance operations are scheduled according to the wind farm operator's decision strategy and will depend on the type of turbines used. Corrective maintenance needs to be conducted due to unexpected failures in the system. In a deterministic model, these failures are assumed to be known at the beginning of the planning activities.PM and CM operations involve three different activities: Transportation of crew, shifting of equipment and various parts and lifting activities. Each of these activities requires different types of vessels. A certain vessel may have many crews on board to work on multiple turbines simultaneously. However, the safety regulations and the capacity of certain vessels limit the number of crews on one vessel to four. Thus a maximum of four activities can be executed using a single vessel.

There are several types of vessels used during the planning horizon which can be chartered such as crew transfer vessels (CTVs), supply vessels, crane vessels and helicopters. Each vessel type has a given speed, loading capacity for spare parts and personnel. The vessels are assigned to a particular base which can either be an onshore or an offshore station.

One of the major uncertain parameters for vessel fleet composition are the weather conditions, such as wind speed and direction, wave height and its direction, current. These determine if the operation can be executed or not and if the vessels on maintenance activities need to return back safely. The varying spot prices for chartering the vessels and the number of uncertain failures for corrective maintenance operations are also considered as uncertain parameters.[3]

Based on the requirements for the operations and maintenance a small vessel database can be created by the moderator consisting of various types of vessels. This database serves as a constraint to the decision maker to operate within the limits of available vessels and crew. One such example of a database can be seen in table 3.5.

Table 3.5: Vessel database [3]

Vessel Type	Passengers	Wind restriction (m/s)	Wave restriction (m)	Speed (m/s)	Number of vessels
CTV	12	30	1.5	48	3
Supply vessel (Small)	21	30	2.5	20	1
Jack up vessel	72	35	2.5	15.4	1

The crews available for the maintenance activities are considered to be groups of 3 with a working shift of 12 hours. For this study, 6 crews are considered.

The main transportation means to the wind turbines is workboat referred as crew transfer vessel (CTV). The access to the wind turbines by CTVs is constrained by significant wave height and the wind speed

A range of vessels is used during the construction, maintenance and operations of offshore wind farms.The majority of these vessels work in different markets but CTVs are used to transport wind farm technicians and other personnel out to sites on daily basis. The majority of the CTVs are designed to be efficient and effective and built to work in the sector. They are usually aluminium catamarans which can accommodate 12 passengers and can have transit speeds from 15-25 kn (28-46 kph). CTVs are driven by pitched propellers and some of them are fitted with jets as they make the vessel more manoeuvrable. Passenger comfort on board is considered a top priority as technicians need to be in good shape as they arrive for the maintenance. Vessels are coded and classified ensuring that they are built and equipped to a recognised standard enabling the charterer to be sure that the vessel meets their requirements.

New vessel designs are continually being developed to meet the changing market. Vessels have increased in size as the bigger vessels provide better sea keeping qualities as well as higher payload capacity. The number of passenger seats is also increasing but the increase in the number of passengers more than 12 calls for a more stringent regulation to the build which adds to the manufacturing cost. The last few years have seen a tremendous expansion of the crew transfer market and a steady evolution of designs as well. As mentioned earlier, the decision maker is constrained by the vessel and crew database and the planning requires certain inputs by the decision maker which are briefed in table 3.6.

Table 3.6: Inputs for transportation by vessels

S. No.	Name	Description	Unit
1	Type of vessel	CTV/ supply vessel/jack-up vessel	N/A
2	No of vessels	size of the fleet	
3	Operational speed	Speed at maximum continuous power	knot or km/hr
4	Max Op. wave height	Limiting wave height	m
5	Max Op. wind speed	Limiting wind speed at sea level	m/s

3.4. WEATHER WINDOWS

The majority of offshore operations are carried out by specialised ships that must be hired for the duration of the operation. Therefore, offshore wind farm accessibility and costs of offshore activities are primarily driven by the expected number of operational hours offshore and waiting times for weather windows, suitable for offshore operations. Having more reliable weather window estimates would result in better wind farm accessibility predictions and, as a consequence, potentially reduce the cost of offshore wind energy. To carry out the maintenance operations, the availability of favourable weather conditions is of the utmost importance. Most of the studies rely on estimating offshore wind farm accessibility by using constraints on maximum allowable met-ocean conditions, such as significant wave height, wave peak period or wind speed. These three parameters are typically used as constraints because they correlate with met-ocean parameters usually provided by weather forecasts. Many studies suggest a reference case of offshore wind turbine maintenance models, where individual limits for significant wave height and wind speeds are used. Typically, the offshore wind farm accessibility depends on the choices of access/ installation vessels and their respective weather limits. Various papers and authors suggest different significant wave height and wind speed limits depending on the activities performed. For example, the blade removal procedure is prohibited for wind speeds above 7 m/s, and working on nacelle is limited by wind speed of 15 m/s. Generally, the significant wave height limit is used during the transportation from port to offshore wind farms by CTVs and the wind speed limits are used for the safe working environment for the technicians at wind turbine hub height.In addition, wave height limits are also important for the docking operations of the vessels with the wind turbines. Wu demonstrates that the smaller vessels have lower operational limits compared to the bigger vessels and thus lower operation capacity throughout the year [27]. The majority of O&M studies use simple met-ocean parameters such as significant wave height and wind speeds to determine the weather windows. Operations are assumed safe to execute when all the relevant met-ocean parameters are below prescribed limits and not safe if either of those limits is exceeded [28].

In the current study, the decision maker can decide on the significant wave height and wind speed limits for a particular vessel and obtain the weather windows in which the vessel can operate and the technicians can carry out the repair activities safely.

An example of such weather windows for a particular CTV in service is displayed below in figure 3.4. The CTV in consideration has a wind speed operation limit of 30 m/s and wave height operation limit of 2 m. The shift hours for the technicians can also be controlled by the moderator by controlling the size of the shift per day and the start and end of the everyday shifts. This can be seen in figure 3.4 where the green line indicates the start of the shift and the red line indicates the end of the shift which is of 12 hours every day. Figure 3.4 also explains the safe travel conditions for the vessel with a safety index which is **1** being safe to travel and **0** being unsafe to travel at the corresponding hours of the scheduling period mentioned on the x-axis.

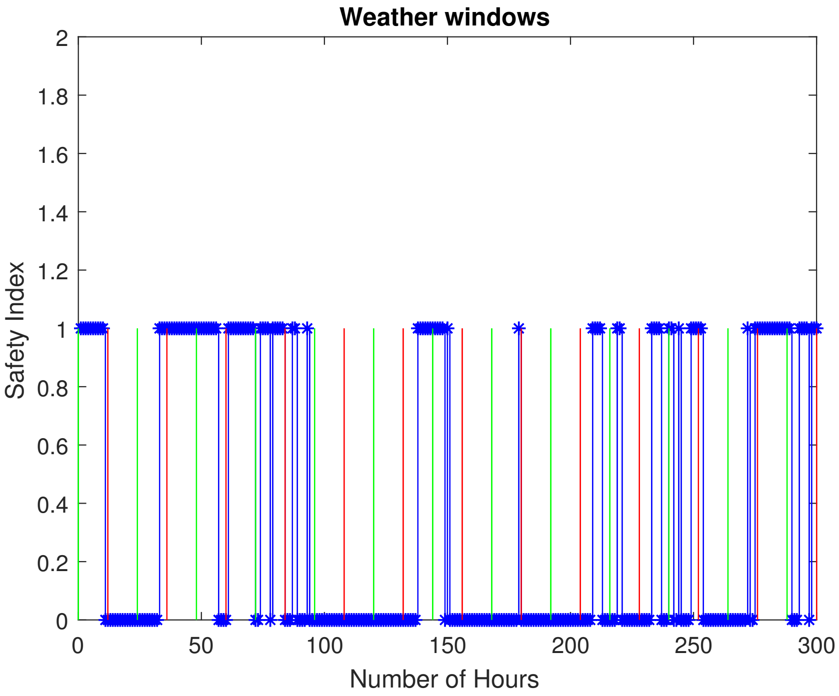


Figure 3.4: Example of Weather windows for a forecast of 300 hours

3.5. WIND FARM LAYOUT

A wind farm layout is generated for the visual aid of the user which include the turbine locations which are represented by global coordinates i.e. latitudes and longitudes. An example of a wind farm layout with 30 turbines and a base can be seen below in figure 3.5.

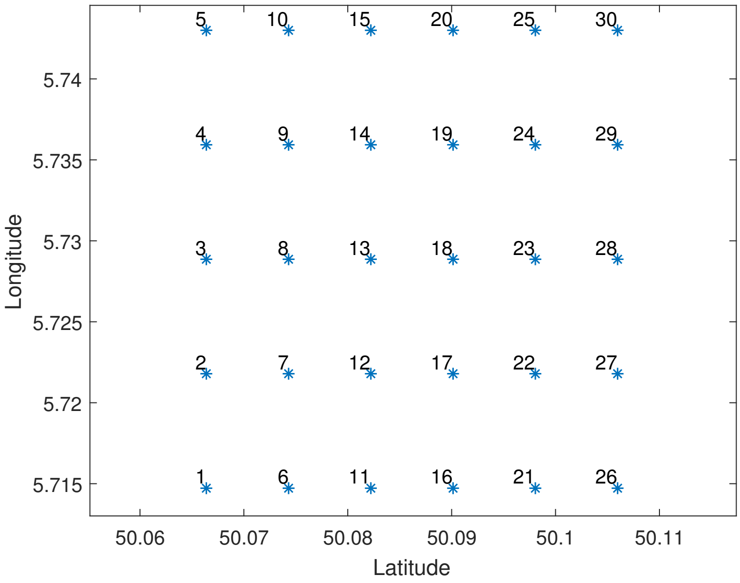


Figure 3.5: Wind Farm layout

3.6. WIND TURBINE FAILURES AND ITS CHARACTERISTICS

While studying the logistic for wind energy systems, it is relevant to study the important subsystems of the WT. The failures of the critical subsystems of the WT are mentioned.

The failure of a wind turbine component can occur due to various reasons. The WTs are designed and tested according to the industry standards and these tests cannot accurately predict all the environmental factors which vary from site to site or the degeneration of the WTs all the possible reasons which can occur during the operational lifetime of the WTs. Thus it is important to study the likely failure characteristics of the WTs in the actual environment. A study by ECN on the failure behaviour of the wind turbines in the Netherlands is presented below in figure 3.6 which shows that the blade failures, generator failures, and gearbox failures contribute together more towards the costs and the downtime [29].

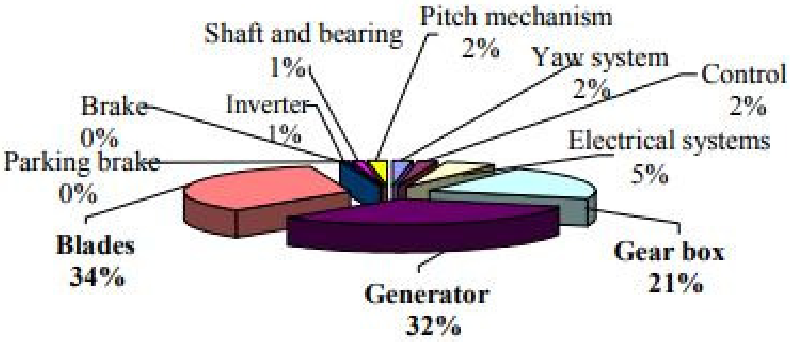


Figure 3.6: Contribution to the offshore wind turbines failures in the Netherlands

The failures occurring in various components of the WT can be summarised and categorised into sections which are detailed in table 3.7.

Each category deals with different types of failures and they are distinguished based on the type of repairs and their complexity along with the time required to carry out the repair actions.

With the list of failures in hand, the decision maker can decide as to which vessels to be used and which turbines will be visited by that vessel. This is decided based on the database of the vessel fleet.

Table 3.7: Description of different failure categories

Failure category	**Description**	**Repair hours required**	**Vessel type**	**Technicians needed**
A	Repair, cleaning, no replacement	3	CTV	2
B	Repair, cleaning, replacements of consumables	3	CTV	3
C	Replacement of small parts	10	CTV	3
D	Replacement large parts >50 tonnes	96	Crane ship	5
E	Replacement rotor, nacelle, yaw, main bearing <300 tonnes	96	jack-up vessel	5
F	Diagnosis	1	CTV	2

3.7. WIND FARM STATUS

3.7.1. VESSEL AND PATH SELECTION

The user has an option to select the vessel for a particular group of repair operations and the path it must follow. The routes followed by the vessels are assumed to start and end at the onshore or offshore base.

The distance between two points is calculated using the Haversine formula.

The **haversine formula** is an important equation used in navigation. It can give the circle distances between two points on a sphere from their latitudes and longitudes [30].

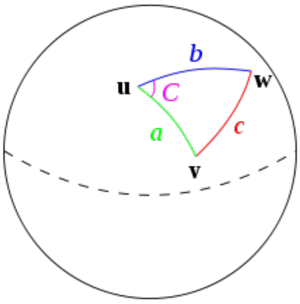


Figure 3.7: Haversine formula to calculate distance between two points on earth

Figure 3.7 illustrates two points on the globe namely u and v which are represented by their respective latitudes and longitudes. The distance 'b' between them is obtained using equations 3.15 to 3.19 where R is the radius of the earth which is 6373 km.

$$\text{dlon=lon2-lon1} \tag{3.15}$$

$$\text{dlat=lat2-lat1} \tag{3.16}$$

$$a = \left(\sin\left(\frac{dlat}{2}\right)\right)^2 + \cos(lat1) * \cos(lat2) * \left(\sin\left(\frac{dlon}{2}\right)\right)^2 \tag{3.17}$$

$$c = 2 * a\tan 2\left(\sqrt{a}, \sqrt{(1-a)}\right) \tag{3.18}$$

$$\text{b=R*c} \tag{3.19}$$

Note: The above-mentioned equations do not consider the non-spheroidal (ellipsoidal) shape of the Earth. It will tend to overestimate trans-polar distances and underestimate trans-equatorial distances. The values used for the radius of the Earth (3961 miles or 6373 km) are optimised for locations around 39 degrees from the equator (roughly the Latitude of Washington, DC, USA).

The test bench requires certain inputs by the decision maker to carry out the maintenance plan. The inputs consist of the vessels and crews to consider and also the turbines to be visited and the order decided by the decision maker. These inputs are summarised in table 3.8. The decision maker has to decide on the purpose of the vessel that has to be deployed. The purpose can either be drop-off or pick-up. The drop-off consists of vessels carrying the crews from the base and drops them off at the turbines under the maintenance planning and similarly, the pick-up consists of picking up of the crews from the turbines at the end of the maintenance schedule and drop them off at the base. In table 3.8, the inputs for maximum operational wave height and wind speeds for the vessels can overrule the data given in the database but the decision maker is recommended to use the values from the database (table 3.5).

Table 3.8: Inputs for vessel and path selection

S. No.	Name	Description	Unit
1	Purpose of the vessel	Drop off/ Pick up action performed by the vessel	N/A
2	Type of vessel	CTV/ supply vessel/jack-up vessel	N/A
3	Crews on the vessel	Number of crews on the vessel to the OWF	N/A
4	Max Op. wave height	Limiting wave height	m
5	Max Op. wind speed	Limiting wind speed at sea level	m/s
6	Drop-off/ Pick-up order	The turbines to be visited by the vessel	N/A
7	Start time of the drop-off/ pick-up order	The time when the vessel leaves the base to drop-off/ pick-up the crew at the turbines	N/A

3.7.2. ACCESS TO THE OFFSHORE WIND FARMS

One of the major hurdles in the O&M of OWF is getting the technicians on and off the turbines and offshore substations safely to carry out work. Two major factors influencing this are:

- *Transit time:* This is the time taken by the vessels to shuttle the service crew from the operating base to the place of work.The limited shift hours available influences the amount of time actually spent on working to maintain the turbine as the transportation time takes away a large portion of the available time. The further the project site, longer the travel time and less time spent on work by the crew.
- *Accessibility:* The proportion of the time a turbine can be easily accessed by the vessel is dependent on the weather conditions. If the weather conditions are usually

higher than the operating thresholds of the vessels then the accessibility to is greatly reduced.

Both these factors depend on the average weather conditions in a particular location - accessibility more so than transit time. Accessibility is critical for unscheduled maintenance since the decision maker will have no opportunity to plan any production outages for times of calmer weather conditions. The planning for O&M often involves efforts to reduce the total cost by seeking ways to reduce the transit time and increase the accessibility to the turbines [31].

The time involved in transferring the service crew from the vessel onto the turbine is very essential. Access time is a parameter describing the time it takes from when the vessel is in the vicinity of the turbine to when the last technician is on the turbine with the equipment to start working. The same time is assumed for picking up the technicians from the turbine after the work is done which is known as the exit time [32].

The access and exit time for CTVs are taken as 15 minutes [32].

3.8. DOWNTIME CALCULATION

The most important issue for any wind park operator is to ensure the constant availability of turbines when the wind is blowing. [33]

Downtime calculations are used to assess the failure severity. A statistical value for downtime is MTTR (Mean time to repair) which is the average time required for a subassembly to recover from any failure.

Onshore wind turbines suffer from a larger number of failures, which can be easily resolved with a small effect on downtime. Offshore WT technology has been directly derived from the onshore counterpart and similar failures can be expected but under offshore conditions, the accessibility is limited which can result in increased downtime.

The following part deals with several terms that are related to the downtime and availability.

- *Reliability* The probability of a device performing its purpose adequately for the period of time intended under the operating conditions encountered.
- *Availability* The probability of finding a system in the operating state at some time into the future.
- *Mean time between failures* This term defines the mean time between two failure in hours for a given population [34].
- *Mean time to failure* This value is very similar to MTBF and is used while evaluating non-repairable systems. MTBF is used for systems that experience repair after every failure. For non-repairable systems, MTTF is considered as the device fails once and MTTF represents the average time for the failure [34].

The relation between MTBF, MTTF and MTTR is illustrated in Figure 3.8

Expected number of failures per turbine per year can be obtained from 3.20

$$N_f = \frac{8760}{MTBF} \tag{3.20}$$

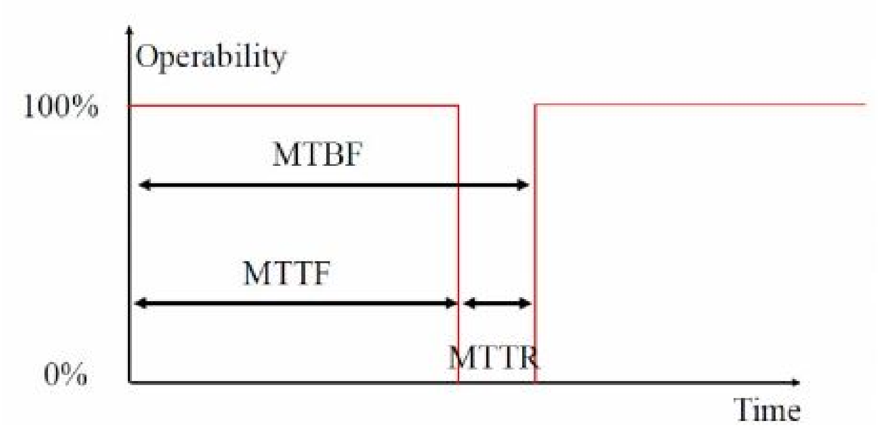


Figure 3.8: Relation between MTBF, MTTF & MTTR [2]

The downtime per turbine per year can be calculated as follows 3.21

$$T_{down} = N_f * MTTR \tag{3.21}$$

4

CASE STUDIES

This chapter deals with the case studies that were performed using the test-bench to answer the thesis objective discussed in section 1.6. A set of 2 case studies are done to analyse the decisions made using the test bench. The first case is used to assess the workability of the test-bench and if it can be trusted. The second case tests the usefulness of the test-bench which comprises of comparison of different decisions on the downtime of the turbines.

4.1. OFFSHORE WIND FARM LAYOUT

Over the course of this case study, an OWF layout consisting of 30 WTs is considered and the NREL 5 MW reference turbine is considered as the WTs in the OWF. Some of its basic specifications are mentioned below in table 4.1.

Table 4.1: Technical specifications & data for the NREL 5MW wind turbine [4]

Rated Power	5MW
Cut-in wind speed	3 m/s
Rated wind speed	11.4 m/s
Cut-out wind speed	25 m/s
Rotor diameter	126 m
Hub height	90 m

Wind turbines in offshore wind farms are usually spaced somewhere between 5D and 9D apart in the prevailing wind direction and between 3D and 5D apart in the direction perpendicular to the prevailing wind direction [35]. Here, the spacing used is 5.5D in sideways direction and 7D in downwind direction. The layout of the OWF can be seen in figure4.1. Here the 30 WTs along with the operating base can be seen. The onshore/offshore operating base is usually 10 km to 18 km.

The functioning of the test-bench comprises actions from two persons, namely, moderator and the decision maker or user. The role of the moderator is to set up the working

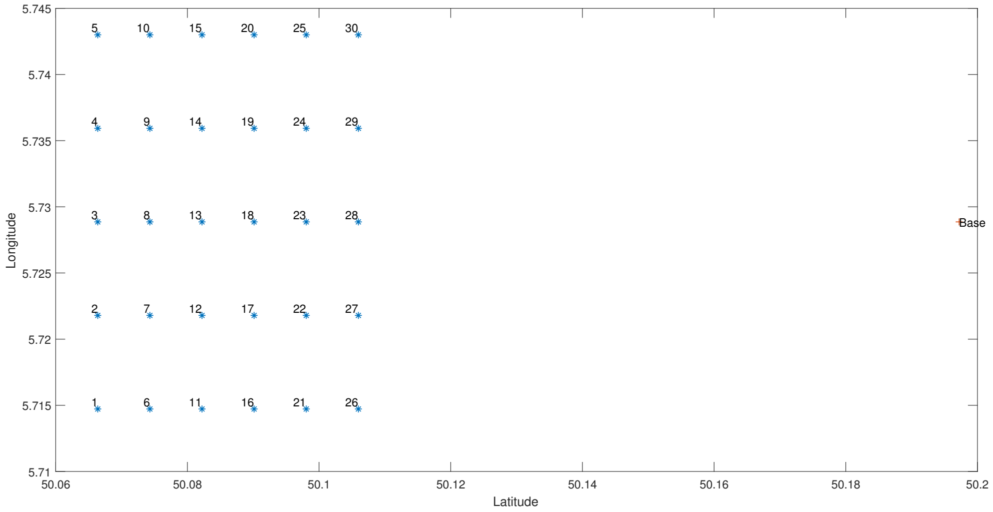


Figure 4.1: Offshore wind farm layout

conditions for the user and the user makes use of these working conditions to determine the logistics decisions for the O&M of OWF.

Table 4.2: Test bench input parameters by the moderator

S. No.	Input	Description
1	Probability Transition Matrices	The transition probability matrix for wind speed forecast is from table 3.2. The transition probability matrix for the significant wave height forecast is from table 3.4
2	Failure properties	This refers to the failure list categories from table 3.7 and the randomly generated failure list for the OWF in consideration can be seen.
3	Wind Turbine Coordinates	Based on these individual coordinates of the WTs on the wind farm and the onshore/offshore base. The layout of the OWF is obtained which acts as a visual aid to the decision maker.
4	Vessel and crew database	The user has the flexibility to decide the fleet size and composition and other required parameters such as the number of crew and vessels, type of vessels, their respective operational speeds and their maximum operational wind speed and significant wave height.

4.2. CASE STUDY 1

The first case is used to assess the workability of the test-bench and if it can be trusted.

The study here has been divided into two sub-cases, where the effects of different parameters on the decision making are observed. The wind farm location and the OWF layout is considered to be the same for both the sub-cases which are fig. 4.1. Here, the decision maker has to decide on the maintenance action based on the weather forecast. This study considers the test-bench input parameters as mentioned in section 2.

4.2.1. CASE 1A

This sub-case studies the effects of change in weather prediction on the planning process. In this sub-case, the input parameters such as the failure list, WT coordinates and the vessel and crew database are kept constant whereas the weather forecasts are varied from good weather prediction with higher accessibility to bad weather prediction with lower accessibility for the vessels.

The moderator sets up the scenario for the decision maker. A good weather forecast 4.2 for a week (168 hours) is generated using the probability transition matrix and a random failure list at the starting of the planning phase is observed as shown in table 4.3.

Based on the wind turbine coordinates given by the moderator, the OWF layout 4.1 is considered.

The vessel and crew database as set up by the moderator is shown below in table 4.4 which remains unchanged throughout this case study.

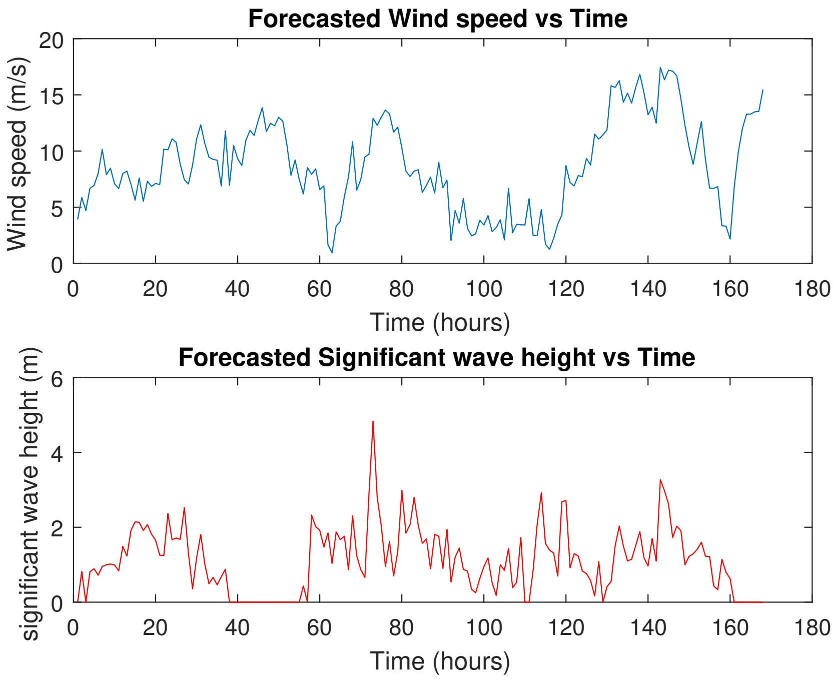


Figure 4.2: Good weather forecast

Upon observing table 4.3 and figure 4.3, the maintenance plan is established to visit the turbines 1,5,10 and 11. Since the weather is good, the planning is expected to run smoothly without any hindrance. The number of crews and vessels are sufficient to carry out the re-

Table 4.3: Failure list

Failed WTs	Failure category	Repair time (hrs)
1	'A'	3
2	'F'	1
4	'F'	1
5	'A'	3
6	'C'	10
7	'C'	10
10	'A'	3
11	'A'	3
16	'A'	3
18	'A'	3
19	'A'	3
20	'A'	3
23	'A'	3
29	'A'	3

Table 4.4: Vessel and crew database

		Vessel Database	
Vessel Type	**Passengers**	**Wave restriction**	**Wind Restriction**
CTV	12	2	30
Supply vessel	40	2.5	30
Jack-up vessel	72	2.5	35

Control Parameters	Value
Fleet size	3 CTV
Number of crews	6
Number of crews on vessel	4

pair activities as seen from table 4.4. Two-part planning is carried out namely: drop-off and pick-up. The process of carrying out the maintenance activity by the crew mainly involves three phases, which are, access phase, where the crew is transferred from the vessel to the turbine, repair phase, where the crew repairs the failure in the turbine and exit phase, where the crew exits the turbine and transfers to the vessel. A simultaneous planning, which involves multiple vessels being deployed at the same time is not considered for the simplicity of the case study.

Table 4.5 gives the overview of the inputs the decision maker gives for the drop-off in the planning process and after which the operations are carried out. Certain results which are observed during drop-offs such as the time spent by the crew on the turbines and the time taken by the vessels to move around in the wind farm and during pick-up which can be observed below in table 4.7 and table 4.8.

The status of the planning can be observed below in table 4.9 which shows the status and position of both the vessels from the start to the end of the maintenance period. For the vessels, '0' in the status means that the vessel in motion and not at any turbine or base at that particular time. The status and position of the crews on different turbines can also be observed in this table. For the crews, '0' means that the crew is not on the turbine, they

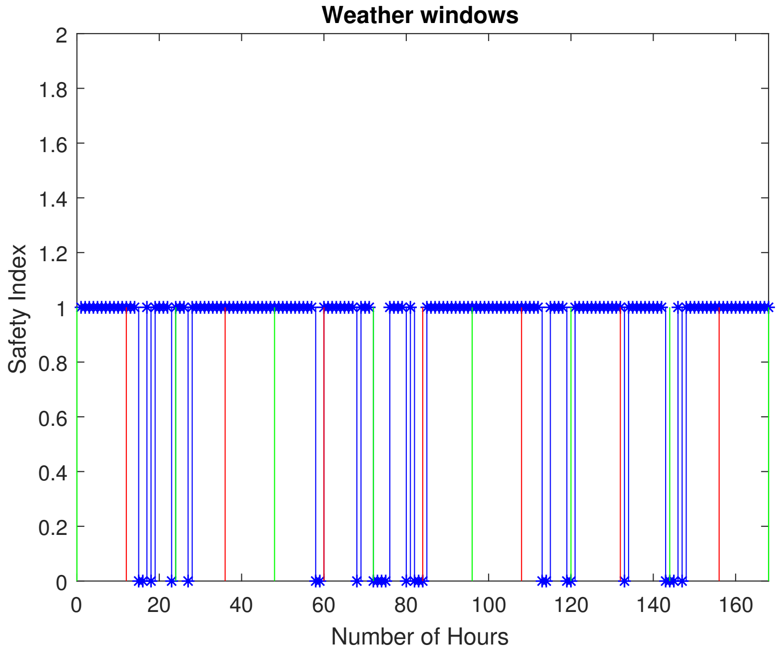


Figure 4.3: Vessel accessibility during good weather

Table 4.5: Inputs for Drop-off

S. No.	Name	Description	Input
1	Purpose of the vessel	Drop off/ Pick up action performed by the vessel	Drop-off
2	Type of vessel	CTV/ supply vessel/jack-up vessel	CTV
3	Crews on the vessel	Number of crews on the vessel to the OWF	3
4	Max Op. wave height	Limiting wave height	2 m
5	Max Op. wind speed	Limiting wind speed at sea level	30 m/s
6	Drop-off order	The turbines to be visited by the vessel	1;5;10;11
7	Start time of the drop-off order	The time when the vessel leaves the base to drop off the crew at the turbines	0100 hrs

Table 4.6: Inputs for Pick up

S. No.	Name	Description	Input
1	Purpose of the vessel	Drop off/ Pick up action performed by the vessel	Pick-up
2	Type of vessel	CTV/ supply vessel/jack-up vessel	CTV
3	Crews on the vessel	Number of crews on the vessel to the OWF	3
4	Max Op. wave height	Limiting wave height	2 m
5	Max Op. wind speed	Limiting wind speed at sea level	30 m/s
6	Pick-up order	The turbines to be visited by the vessel	1;5;10;11
7	Start time of the pick-up order	The time when the vessel leaves the base to pick up the crew from the turbines	0400 hrs

are either on the vessel or on the base and '1' refers to the crew being on the turbine. For example, it can be clearly seen that the drop-off vessel starts from the base at 0100 hours and reaches the first turbine which is turbine number 1 at 0150 hours and the technicians

Table 4.7: Time spent by the crew during access, repair phase and exit phase

Wind Turbine	Failure Category	Access Time (hrs)	Repair Time (hrs)	Exit Time (hrs)	Total Time (hrs)
Access and repair phase					
1	A	0.25	3	-	3.25
5	A	0.25	3	-	3.25
10	A	0.25	3	-	3.25
11	A	0.25	3	-	3.25
Exit phase					
1	A	-	-	0.25	0.25
5	A	-	-	0.25	0.25
10	A	-	-	0.25	0.25
11	A	-	-	0.25	0.25

Table 4.8: Vessel motion during drop-off and pick-up

Start position	**End position**	**Distance (km)**	**Time (hrs)**	**Cumulative time (hrs)**
Drop-off				
1	5	2.02	0.042	0.25
5	10	0.88	0.02	0.5
10	11	2.2	0.05	0.75
Pick-up				
1	5	2.02	0.042	0.25
5	10	0.88	0.02	0.5
10	11	2.2	0.05	0.75

transfer from the vessel to the turbine where they carry out the repair activity for 3 hours and when the pick-up vessel is deployed, the crew is picked up at 0450 hours, exactly after 3 hours of repair. This can be observed for other crews working on turbine number 5, 10 and 11 as well and the status shows that the planning done at the initially matches the status at the end.

From table 4.9, the downtime of the turbines in consideration can be calculated. The downtimes of these turbines can be observed in 4.10. Other failed turbines remain down until they are repaired which can be carried out using the same planning procedure when there is a sufficient accessibility for the vessels and during the working shift hours of the technicians.

Table 4.9: Status of the planning at the end of the planning phase

Hours	**Crew1**	**crew2**	**crew3**	**crew4**	**Drop-off vessel**	**Pick-up vessel**
1	0	0	0	0	Base	0
1.25	0	0	0	0	0	0
1.5	0	0	0	0	1	0
1.75	1	0	0	0	1	0
2	1	0	0	0	5	0
2.25	1	1	0	0	5	0
2.5	1	1	0	0	10	0
2.75	1	1	1	0	10	0
3	1	1	1	0	11	0
3.25	1	1	1	1	11	0
3.5	1	1	1	1	0	0
3.75	1	1	1	1	Base	0
4	1	1	1	1	0	Base
4.25	1	1	1	1	0	0
4.5	1	1	1	1	0	1
4.75	0	1	1	1	0	1
5	0	1	1	1	0	5
5.25	0	0	1	1	0	5
5.5	0	0	1	1	0	10
5.75	0	0	0	1	0	10
6	0	0	0	1	0	11
6.25	0	0	0	0	0	11
6.5	0	0	0	0	0	0
6.75	0	0	0	0	0	Base
7	0	0	0	0	0	0
7.25	0	0	0	0	0	0
7.5	0	0	0	0	0	0
7.75	0	0	0	0	0	0
8	0	0	0	0	0	0

Table 4.10: c

WT#	**Downtime (hrs)**
1	5.5
5	6
10	6.5
11	7

A similar case can be observed when the weather prediction (fig 4.4) is worsened for the same list of failure, OWF layout and vessel and crew database. The accessibility of the OWF for the CTVs is reduced considerably.

The same maintenance plan is established as before, i.e. visiting the turbines 1,5,10 and 11. But due to the unavailability of enough weather windows to carry out the repair activities for these four turbines, the decision maker has to limit the number of turbines to be repaired to three.

A similar approach to the one before is followed where the inputs in table 4.5 and table 4.6 are the same except the drop-off order and the pick-up order which is now changed to 1,5 and 10. The start time for both the vessels is also changed to 2400 hrs and 2700 hrs respectively due to the inaccessibility for the first 24 hours because of the bad weather.

The programme provides us with all the necessary information such as the time spent by the crew on the turbines and the time taken by the vessels to move around in the wind farm during drop-off and pick-up whose results can be observed in Appendix A.

The status of the planning can be observed in table 4.11. It can be clearly seen that the planning matches the status of the planning.

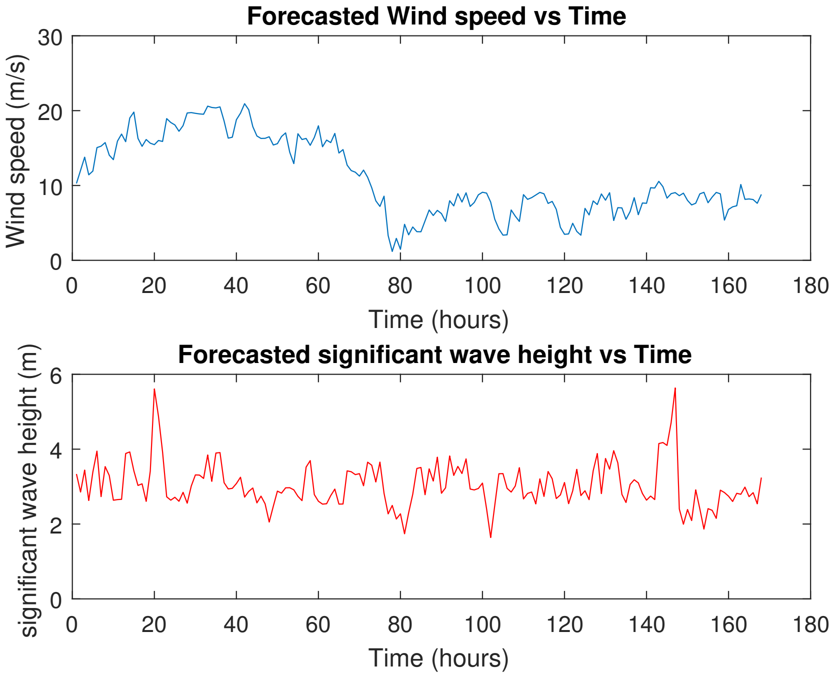


Figure 4.4: Bad weather forecast

The bad weather decreases the accessibility of the OWF for the vessels which reduces the number of turbines repaired which can lead to increased downtime of the turbines in the farm. The downtimes for the turbines repaired in this case can be observed in table 4.10. It is evident from the table that due to the decrease in the accessibility of the wind farm, the repair process started very late which added to the downtime of the turbines.

Thus, it can be concluded that the change in weather prediction can greatly affect the planning process and the downtime of the OWF.

Table 4.11: Status of the planning at the end of the planning phase

Hours	Crew1	crew2	crew3	Drop -off vessel	Pick-up vessel
0-23.75	0	0	0	0	0
24	0	0	0	Base	0
24.25	0	0	0	0	0
24.5	0	0	0	1	0
24.75	1	0	0	1	0
25	1	0	0	5	0
25.25	1	1	0	5	0
25.5	1	1	0	10	0
25.75	1	1	1	10	0
26	1	1	1	0	0
26.25	1	1	1	Base	0
26.5	1	1	1	0	0
26.75	1	1	1	0	0
27	1	1	1	0	Base
27.25	1	1	1	0	0
27.5	1	1	1	0	1
27.75	0	1	1	0	1
28	0	1	1	0	5
28.25	0	0	1	0	5
28.5	0	0	1	0	10
28.75	0	0	0	0	10
29	0	0	0	0	0
29.25	0	0	0	0	Base
29.5	0	0	0	0	0

Table 4.12: Downtime of the repaired turbines

WT#	Downtime (hrs)
1	27.5
5	28
10	28.5

4.2.2. CASE 1B

This sub-case shows the effect of a change in the vessel and crew database on the downtime of the OWF. Here, two sets of vessel and crew databases are considered for the same list of failures and weather prediction. The input parameters for the drop-off and pick-up are the same as viewed in section 4.2.1 except for the order of the turbines to be visited for repair. A weather forecast of 2 weeks (336 hours) is considered for both the set of databases which can be seen in 4.5 and a random failure list in consideration is in table 4.13. This case study is performed on the same wind farm layout as in case 1A. The weather windows for the accessibility of the OWF for the vessels can be generated for the vessels in consideration and can be observed in figure 4.6.

From the figures 4.5, 4.6 and table 4.13 a maintenance plan can be established to visit

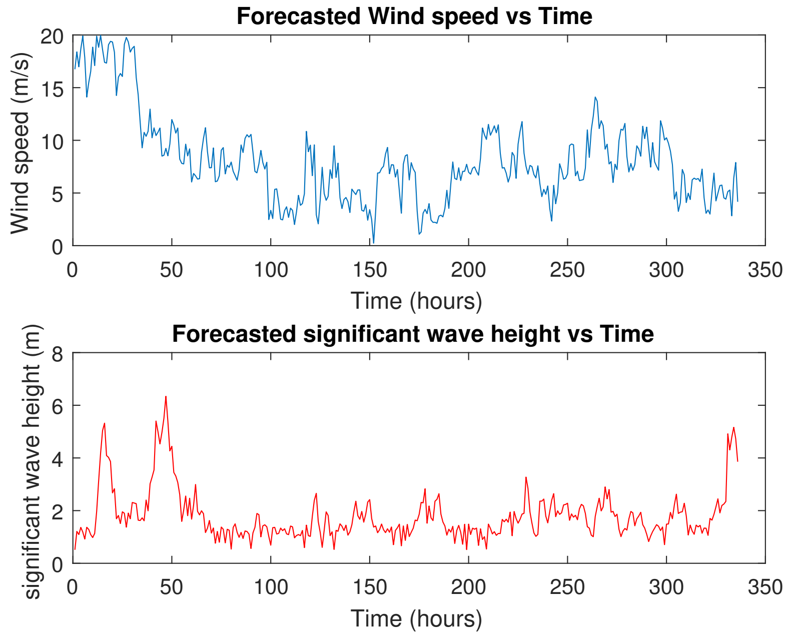


Figure 4.5: Weather forecast for case 1B

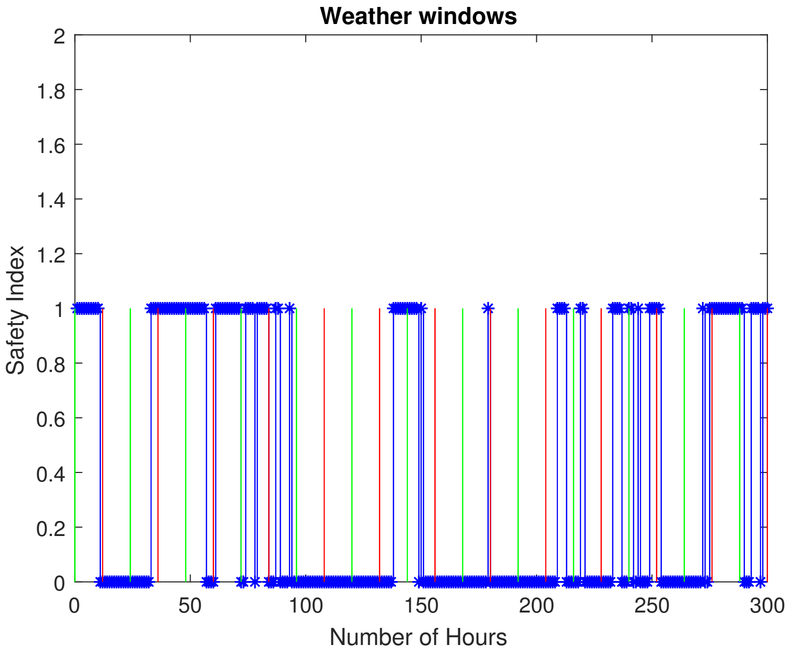


Figure 4.6: Vessel accessibility

the turbines 2,3,6 and 7. The weather windows clearly show that the weather is going to be good for the transportation of vessels for the first 12 hours and many maintenance activities can be carried out during this time period. The same procedure of drop-off and pick-up is followed here. For the first part of this case study, we consider 2 CTVs along with 4 crews of 3 technicians each.

The time spent by the crew during all the working phases and the motion of the vessel

Table 4.13: Failure list for case 1B

Failed WTs	Failure Category	Repair Time (hrs)
2	A	3
3	A	3
5	C	10
6	A	3
7	A	3
8	A	3
9	A	3
10	A	3
12	A	3
14	F	1
15	A	3
17	A	3
18	F	1
20	A	3
21	A	3
22	A	3
25	A	3
26	A	3
28	A	3
29	F	1

during the planning period can be seen in Appendix A The status of the planning can be observed in table 4.14 which shows the status and positions of both the vessels and the crews during the maintenance period.

The downtimes of the turbines repaired can be calculated and documented as below in table 4.16.

Table 4.14: Status of the planning

Time	Crew 1	Crew 2	Crew 3	Crew 4	Drop-off vessel	Pick-up vessel
1	0	0	0	0	Base	0
1.25	0	0	0	0	0	0
1.5	0	0	0	0	2	0
1.75	1	0	0	0	2	0
2	1	0	0	0	3	0
2.25	1	1	0	0	3	0
2.5	1	1	0	0	6	0
2.75	1	1	1	0	6	0
3	1	1	1	0	7	0
3.25	1	1	1	1	7	0
3.5	1	1	1	1	0	0
3.75	1	1	1	1	Base	0
4	1	1	1	1	0	Base
4.25	1	1	1	1	0	0
4.5	1	1	1	1	0	2
4.75	0	1	1	1	0	2
5	0	1	1	1	0	3
5.25	0	0	1	1	0	3
5.5	0	0	1	1	0	6
5.75	0	0	0	1	0	6
6	0	0	0	1	0	7
6.25	0	0	0	0	0	7
6.5	0	0	0	0	0	0
6.75	0	0	0	0	0	Base

From the status in table 4.14, it is clearly visible that the vessels and the crews returned by 0700 hours and since we have good working conditions till 1200 hours, another planning can be done based on the failure list in 4.13. Upon looking at the failure list and the weather windows, a new planning can be done to repair more turbines in the available time.

Using the available time, another planning is made for turbines 8, 9 and 10. At the end of the previous planning, all the vessels and crews are safely back at the base and another planning is started after a buffer time of 30 minutes for refuelling and rest for the crew. The next planning is started at 0730 hours and ends at 1225 hours which is evident from the status in table 4.15. Since the working time exceeds the shift time of 12 hours a day, the crew and the vessel operators may be subjected to extra pay for overtime.

Table 4.15: Status of the planning at the end of planning phase

Time	Crew 1	Crew 2	Crew 3	Drop-off vessel	Pick-up vessel
7	0	0	0	Base	0
7.25	0	0	0	0	0
7.5	0	0	0	8	0
7.75	1	0	0	8	0
8	1	0	0	9	0
8.25	1	1	0	9	0
8.5	1	1	0	10	0
8.75	1	1	1	10	0
9	1	1	1	0	0
9.25	1	1	1	Base	0
9.5	1	1	1	0	0
9.75	1	1	1	0	0
10	1	1	1	0	Base
10.25	1	1	1	0	0
10.5	1	1	1	0	8
10.75	0	1	1	0	8
11	0	1	1	0	9
11.25	0	0	1	0	9
11.5	0	0	1	0	10
11.75	0	0	0	0	10
12	0	0	0	0	0
12.25	0	0	0	0	Base

The downtimes of the turbines repaired for both the plannings are documented in table 4.16.

Table 4.16: Downtime of all the repaired turbines for a bigger fleet

WT#	Downtime (hrs)
2	4.5
3	5
6	5.5
7	6
8	10.5
9	11
10	11.5

The bigger fleet size aided in performing more activities by the crew and the vessels. A large size of the fleet shows that more repair activities could be performed during the good weather conditions in the OWF.

Now, the fleet size is changed and the number of CTVs and crews is reduced to 1 and 3 respectively. The same procedure is followed. Looking at the list of failures and the weather windows, a planning is scheduled. It is important to note that due to the reduced number of available CTV, the drop-off vessel has to return back to the base after dropping off all the crews and then act as a pick-up vessel when it is picking up the crew at the end of the maintenance period. This result can be viewed in the table 4.17.

Table 4.17: Status of the planning with reduced crew

Time	**Crew 1**	**Crew 2**	**Crew 3**	**Drop-off vessel**	**Pick-up vessel**
1	0	0	0	Base	0
1.25	0	0	0	0	0
1.5	0	0	0	6	0
1.75	1	0	0	6	0
2	1	0	0	8	0
2.25	1	1	0	8	0
2.5	1	1	0	9	0
2.75	1	1	1	9	0
3	1	1	1	0	0
3.25	1	1	1	Base	0
3.5	1	1	1	0	0
3.75	1	1	1	0	0
4	1	1	1	0	Base
4.25	1	1	1	0	0
4.5	1	1	1	0	6
4.75	0	1	1	0	6
5	0	1	1	0	8
5.25	0	0	1	0	8
5.5	0	0	1	0	9
5.75	0	0	0	0	9
6	0	0	0	0	0
6.25	0	0	0	0	Base

Just like the previous situation, a lot of time is left for the shift to end. So another maintenance planning is scheduled and a similar process is followed to repair the turbines 6; 12 and 15. Also, in this case, the sole CTV acts as the drop off the vessel and the pick-up vessel and ends the maintenance for the day at 1250 hours.

Table 4.18: Status of the planning for second shift

Time	**Crew 1**	**Crew 2**	**Crew 3**	**Drop-off vessel**	**Pick-up vessel**
7	0	0	0	Base	0
7.25	0	0	0	0	0
7.5	0	0	0	10	0
7.75	1	0	0	10	0
8	1	0	0	12	0
8.25	1	1	0	12	0
8.5	1	1	0	15	0
8.75	1	1	1	15	0
9	1	1	1	0	0
9.25	1	1	1	Base	0
9.5	1	1	1	0	0
9.75	1	1	1	0	0
10	1	1	1	0	Base
10.25	1	1	1	0	0
10.5	1	1	1	0	10
10.75	0	1	1	0	10
11	0	1	1	0	12
11.25	0	0	1	0	12
11.5	0	0	1	0	15
11.75	0	0	0	0	15
12	0	0	0	0	0
12.25	0	0	0	0	Base

The downtimes of the repaired turbines are recorded in table 4.19. It is also important to note that the planning for the next day is carried out based on the updated forecast and the updated failure list which may not contain the turbines repaired in this period.

Table 4.19: Downtime of all the repaired turbines for a smaller fleet

WT#	Downtime (hrs)
6	10
8	4.5
9	5
10	5.5
12	10.5
15	11

In the case study we see that when the fleet size is bigger, more turbines can be repaired. Although we considered a case where only one planning schedule is being executed in reality, multiple schedules can be carried out simultaneously which would increase the number of turbines repaired thus reducing the downtime of the wind farm and increasing its productivity.

4.2.3. DISCUSSION

In this case study, the workability of the test bench is tested by changing various parameters and seeing its effect in the decisions taken by the decision maker. The first part of this case study consists of analysing the effects of change in weather forecast on the maintenance planning. It was seen that when the weather is good, i.e. more accessibility to the vessels, more turbines were repaired compared to the number of turbines repaired with bad weather. Although the use of the stochastic model for weather and the downtimes of the repaired turbines in both the conditions could not assist in establishing a standard relation between the two aspects, it can be clearly seen that the downtimes vary in both the situations and the good weather prediction gives a better planning opportunity.

The second part of this case study involved the changing of vessel and crew database and studied its effects on the decision makers planning. The conditions were set up to be ideal for the first 12 hours which is the entire shift for a day so that the planning can go uninterrupted. In this, the initial vessel and crew database consist of 3 CTVs, 1 service vessel, 1 jack-up vessel and 6 crews of 3 technicians each. And later this fleet size is reduced to just 1 CTV and 3 crews. Since the simultaneous planning was not adopted, we could not observe any substantial difference in the planning. But it was observed that with the decrease in the fleet size, there was a decrease in the number of turbines repaired as the single CTV which was considered to be transporting all the available crews had to return back to the base as per the assumption in section 2.2. This consumed a lot of time which could have been used in the transportation of many more crews if the database included multiple vessels. The difference in the downtimes can be clearly seen in tables 4.16 and 4.19.

If a simultaneous planning strategy is considered with multiple vessels being deployed at the same time, the number of WTs repaired could increase substantially.

4.3. CASE STUDY 2

4.3.1. OVERVIEW

The following case study has been performed to study the usefulness of the tool. It is to show that it is useful to have the tool that the different strategies will give different results and that you can detect that.

The OWF layout and the specifications of the WTs in consideration are taken from section 4.1. The input parameters for the moderator can be referred from the table section 2.2.1.

The effect of different strategies applied to the same conditions can be observed as the tool provides the results showing how the variations in strategies can affect the planning.

This case study consists of two approaches to planning, conservative and optimistic. So far, we have just considered the failure category 'A' which requires only 3 hours of repair work and needs only CTVs to transport crews. This part of the study considers mainly the failure category 'C' which consists of small replacements and requires only 3 technicians and CTVs to transfer them but such maintenance activities take up 10 hours and a continuous weather window of more than 10 hours is convenient to carry out such maintenance activity.

To perform a 10-hour repair, a planner needs at least 12 hours to carry out the maintenance operations which includes the transportation of the technicians from the base and back. If the weather forecast has exactly 12 hours of available weather windows, the planner may plan the 10-hour repair. This planning can only be executed if the realised weather has the same characteristics as the forecast, meaning, it has 12 or more hours of weather windows at the same time of planning. If for the same forecasts, a planner may opt for a conservative approach where larger weather windows which have more than 12 hours of good weather conditions and the planning is only executable when this is the same for the realised weather as well, i.e. the realised weather also has 12 or more hours of good workable weather at the same time. These two different approaches show a difference in the planning of the maintenance activities and the results from these planning can help us estimate the type and quality of the planning that might be useful for future plannings.

Table 4.20: Fixed parameters for Case study 2

Parameter	Value
Failed WT	1
Failure category	C
Type of Vessel	CTV
No. of crews needed	1
Forecast length	168 hours

The test-bench was used to execute these two planning strategies for 10 different scenarios. All the parameters except the weather forecast were kept the same which can be seen in table 4.20. 10 different forecast were considered for this study and both types of strategies were applied to every forecast and the results were documented based on the observations.

In these 10 weather scenarios, the conservative approach had an equal probability of the planning being executable whereas the optimistic approach had a higher probability of the plan being executed than the conservative one. The conservative approach, out of 10, had 5 scenarios where the plan could be easily executed but the if an optimistic user makes decisions for the same weather scenarios, 6 scenarios came up where the planning could be executed as the weather favoured according to the forecast. And with more favourable situations, the optimistic approach had half the downtime than what was observed during the conservative planning approach.

4.3.2. DISCUSSION

The simulations which were run for various weather forecast based on which plannings were implemented showed some interesting results. There were situations when the optimistic approach led to a successful execution of the planning due to the good realised weather for the assumed weather window and there were some instances where the planning could not be executed due to the bad realised weather which led to increased downtime for the particular turbine. Similar was the case with the conservative planning where the planning could not be executed due to the unfavourable weather conditions at that time. Conservative approach had a fewer number of instance than the optimistic approach where the planning was executed due to good weather conditions.

The results show that there were more instances during the non-conservative planning when the realised weather turned out to be as expected and the repairs were carried out efficiently than with the conservative planning. As the non-conservative planning consisted of using the earliest available weather window for the repairs, the downtime of the turbine in all the favourable situations was lower than compared to the downtimes of the conservative planning.

5

CONCLUSIONS AND RECOMMENDATIONS

This chapter summarises the learnings from this thesis study and gives some recommendations for future work.

5.1. CONCLUSIONS

The objective of this study was to test the effectiveness of the decisions from a decision maker made for the logistics of the maintenance planning in the offshore wind farms. The primary focus was on the development of the test-bench to provide a platform to check if the planning given by the decision maker can be executed effectively or not. The study also consisted of identifying the various important parameter and their effects in the planning decisions. The current study indicates the significance and the potential of short-term decision support to reduce the costs involved in the logistics of O&M of OWF. The main intention of this study is to reduce the downtimes of the WTs in the wind farm which would in turn increase the availability of the wind farm and for this a new state-of-art test-bench was designed and developed.

A significant work has been done in building a test-bench. A test-bench is required to provide certain information like weather forecast, wind farm status and the vessel and crew database to the decision maker and using these information, a decision maker is able to make a maintenance plan. Weather forecast is one of the crucial parts of the planning procedure and for this a consistent (but different) realised weather time series to test the planning is simulated. The generation of the weather forecasts consist of forecast errors which are modelled and added to the realised weather. Furthermore, the wind farm status is very important while making a maintenance plan, and thus the test-bench provides the decision maker with information such as the wind farm layout and the failed turbines which are essential for the planning. Efforts were made to classify different types of failure and the failure rates of every type of failure for the ease of decision maker. Another key aspect of the logistic planning is the vessel and crew database. This provides the decision maker with the information regarding the available fleet and the technicians.

MATLAB was used as a software tool to develop a working test-bench. The weather forecasts were generated using the Markov chains and forecast errors were simulated using the ARMA model. The inputs regarding the positions of the WTs in the OWF provided a basis for the calculation of distance between the turbines and the base for the calculation of transport time for the vessels and crews. The haversine formula is utilised for the distance calculation which incorporates the curvature of the earth to calculate the distance. This gave the flexibility to use the test bench for a large scale OWF or multiple wind farms where the distance can be affected by the earth's curvature.

Once the tool with desired inputs and outputs was developed, the effects of various parameters were studied using the case studies. Here the effect of the change in weather conditions and the size of the fleet are studied against their influence on the downtime of the OWF. It is no surprise that when the weather prediction is good, which means that the realised weather conditions is very similar to the forecast, the planning can go ahead as expected and with more accessibility to the OWF, more repair activities can be performed. The change in the fleet size shows that with decreased number of vessels and crews fewer turbines are repaired thus increasing the downtime of the farm. But with increased number of vessels and crews, more turbines are repaired which can reduce the downtime significantly. To study the trade-off between the optimistic and conservative planning approaches, another case study was executed using the test-bench where these different approaches were adopted for the same scenario and same set of failures. It was observed that in most of the scenarios, the optimistic approach yielded better results than the conservative one.

To summarise, the objective of this study was to test the effectiveness of the decisions. With the results obtained from analysing the case studies, the test-bench can be used to benchmark the decisions taken by the decision maker to plan their short-term maintenance activities in a more effective way.

5.2. RECOMMENDATIONS

The stochastic models were developed with various simplifications for the ease of implementation. Necessary improvements to the tool can be made to check its behaviour against a more specific set of data in terms of weather, failure statistics and other wind farm-related data.

As discussed in chapter 2, the wind speeds and the significant wave heights are not correlated. A study and implementation of consistent correlation between these two elements in the predictions can have a greater impact on the importance of weather in such studies.

Moreover, the study considers only corrective maintenance and the knowledge of preventive maintenance and the non-repairable systems and its inclusion in the planing strategy can also help in improving the functionality of the test bench.

The test bench considers the assumption that the planning given by the decision maker for a particular group of vessels and crews start from the base and end at the base. Therefore, the flexibility to change the planning midway based on the changing weather conditions or the emergence of new failures while the maintenance operations can give a more dynamic approach to the short-term decision support.

A

RESULTS FROM CASE STUDY 1

The results shown below in tables A.1 and A.2 belong to the case study 1A where the planning is executed for a bad weather condition.

Table A.1: Time spent by the crew during access, repair phase and exit phase for case 1A

Wind Turbine	**Failure Category**	**Access Time (hrs)**	**Repair Time (hrs)**	**Exit Time (hrs)**	**Total Time (hrs)**
Access and repair phase					
1	A	0.25	3	-	3.25
5	A	0.25	3	-	3.25
10	A	0.25	3	-	3.25
Exit phase					
1	A	-	-	0.25	0.25
5	A	-	-	0.25	0.25
10	A	-	-	0.25	0.25

Table A.2: Vessel motion during pick-up and drop-off for case 1A

Start position	**End position**	**Distance (km)**	**Time (hrs)**	**Cumulative time (hrs)**
Drop-off				
1	5	2.02	0.04	0.25
5	10	0.88	0.02	0.5
Pick-up				
1	5	2.02	0.04	0.25
5	10	0.88	0.02	0.5

Case study 1B deals with the effect of a change in fleet size on the planning. Here, the tables A.3 and A.4 represent the time spent by the crew during the repair activity and the vessel motion in the farm during the planning as decided by the decision maker. There are two shifts for every planning in this case study and hence, tables A.3 and A.4 show the results for the first shift when the fleet has 3 CTVs and tables A.5 and A.6 show the results during the second shift.

Table A.3: Time spent by the crew during access, repair and exit phase for case 1B first shift (3 CTVs and 6 crews)

Wind Turbine	**Failure Category**	**Access Time (hrs)**	**Repair Time (hrs)**	**Exit Time (hrs)**	**Total Time (hrs)**
Access and repair phase					
2	A	0.25	3	-	3.25
3	A	0.25	3	-	3.25
6	A	0.25	3	-	3.25
7	A	0.25	3	-	3.25
Exit phase					
2	A	-	-	0.25	0.25
3	A	-	-	0.25	0.25
6	A	-	-	0.25	0.25
7	A	-	-	0.25	0.25

Table A.4: Vessel motion during pick-up and drop-off for case 1B first shift (3 CTVs and 6 crews)

Start position	**End position**	**Distance (km)**	**Time (hrs)**	**Cumulative time (hrs)**
Drop-off				
2	3	0.51	0.02	0.25
3	6	1.34	0.03	0.5
6	7	0.50	0.01	0.75
Pick-up				
2	3	0.51	0.02	0.25
3	6	1.34	0.03	0.5
6	7	0.50	0.01	0.75

Tables A.7, A.8 and tables A.9, A.10 give the results during first and second shift respectively. These results are obtained when the fleet and crew size is reduced to 1 and 3 respectively.

Table A.5: Time spent by the crew during access, repair and exit phase for case 1B second shift (3 CTVs and 6 crews)

Wind Turbine	Failure Category	Access Time (hrs)	Repair Time (hrs)	Exit Time (hrs)	Total Time (hrs)
Access and repair phase					
8	A	0.25	3	-	3.25
9	A	0.25	3	-	3.25
10	A	0.25	3	-	3.25
Exit phase					
8	A	-	-	0.25	0.25
9	A	-	-	0.25	0.25
10	A	-	-	0.25	0.25

Table A.6: Vessel motion during pick-up and drop-off for case 1B second shift (3 CTVs and 6 crews)

Start position	End position	Distance (km)	Time (hrs)	Cumulative time (hrs)
Drop-off				
8	9	0.51	0.02	0.25
9	10	0.51	0.02	0.5
Pick-up				
8	9	0.51	0.02	0.25
9	10	0.51	0.02	0.5

Table A.7: Time spent by the crew during access, repair and exit phase for case 1B first shift (1 CTV and 3 crews)

Wind Turbine	Failure Category	Access Time (hrs)	Repair Time (hrs)	Exit Time (hrs)	Total Time (hrs)
Access and repair phase					
8	A	0.25	3	-	3.25
9	A	0.25	3	-	3.25
10	A	0.25	3	-	3.25
Exit phase					
8	A	-	-	0.25	0.25
9	A	-	-	0.25	0.25
10	A	-	-	0.25	0.25

Table A.8: Vessel motion during pick-up and drop-off for case 1B first shift (1 CTV and 3 crews)

Start position	End position	Distance (km)	Time (hrs)	Cumulative time (hrs)
Drop-off				
8	9	0.51	0.02	0.25
9	10	0.51	0.02	0.5
Pick-up				
8	9	0.51	0.02	0.25
9	10	0.51	0.02	0.5

Table A.9: Time spent by the crew during access, repair and exit phase for case 1B second shift (1 CTV and 3 crews)

Wind Turbine	**Failure Category**	**Access Time (hrs)**	**Repair Time (hrs)**	**Exit Time (hrs)**	**Total Time (hrs)**
Access and repair phase					
6	A	0.25	3	-	3.25
12	A	0.25	3	-	3.25
15	A	0.25	3	-	3.25
Exit phase					
6	A	-	-	0.25	0.25
12	A	-	-	0.25	0.25
15	A	-	-	0.25	0.25

Table A.10: Vessel motion during pick-up and drop-off for case 1B second shift (1 CTV and 3 crews)

Start position	**End position**	**Distance (km)**	**Time (hrs)**	**Cumulative time (hrs)**
Drop-off				
6	12	1.02	0.02	0.25
12	15	1.52	0.03	0.5
Pick-up				
6	12	1.02	0.02	0.25
12	15	1.52	0.03	0.5

B

WIND TURBINE COMPONENTS

Different subassemblies are described along with their functionality, critical components, common reason for failure and actions are taken when a failure occurs.

- *Blades*
  Wind turbine blades are used to harness the wind power by rotating and then transferring this rotation energy to the gearbox through a main shaft and the hub. Blades are made of composite materials which are often preferred for their properties of high strength and stiffness to weight ratio [36].Such composite materials also provide resistance to damage in a harsh offshore environment.

  The core of a blade is the part that receives the load and thus it is designed in such a way that it is light and flexible and still be able to withstand such heavy loads [ref]. Fatigue damage and lightning strikes are known to cause cracks on the surface of the blade. Ice build up is also one of the major reasons for failure in fibreglass reinforced plastic (GRP) blades [29].

  It is often difficult to assess the damage on the blades by the sight of cracks or weakening of the support structure and hence the blade is replaced with a new one [37]

- *Hub*
  The hub of a WT connects the blades to the main shaft transmitting the rotational energy to the gearbox. The hub is usually made from steel which is difficult to weld or be casted [36]. The hub design is usually influenced by the design and geometrical features of the WT.

  The hub is connected to the blades using fasteners and bolts made of different materials and thus their interactions during variable loading can cause failures.

- *Pitch System*
  For WTs with pitch regulation, the blades rotate with respect to the hub due to the bearing at the intersection between the hub and the blades. Blades can be pitched individually or by a common pitch mechanism and these are controlled electrically or hydraulically. An electrical pitch uses a slip ring to transfer electric power from the nacelle to the hub whereas the mechanical pitch uses a rotating union to transfer the pressure [36] [37].

Currently, there are more hydraulic pitch in use than the electrical pitch due to the advantage of its higher power density and the need for fewer components [38]. It is usually made sure that the pitch systems work even if the slip rings or rotating union or any other components fail. Therefore, batteries or hydraulic accumulators are installed in the hub as a back up [39].

- *Gearbox*
  The gearbox of a Wt increases the rotational speed of the main shaft from as low as 20-25 revolutions per minute (RPM) to as high as 1500 RPM which is essential to drive the generator of a WT. It is one of the heaviest and most expensive component of a WT. Today's WTs usually use three-stage planetary gearbox [36].

  Gearboxes are made up of shafts, gears, bearings and have a metal cover. The weight of the gearbox increases dramatically with the rated power of the WT. The main load which a gearbox has to handle is the torque from the motor and this load can fluctuate. Loads from the starting of the generator can also affect the gearbox. The main parts of the gearboxes that are most affected are the bearings, gear teeth and seals which can fail and fall off [36] [29] [37]. A lubrication system is used to reduce the fatigue damage to the gearbox.

  Under-dimensioned gearboxes can also be a cause for gearbox failures and this occurs when the manufacturers do not understand the operating conditions completely. Failure or breakage of even a small component of the gearbox calls for a complete and thorough cleaning and testing. The replacements for gearboxes are usually done before the failure [24].

- *Drive Train*
  Drive train consists of a shaft connecting the rotor to the gearbox and further to the generator. These are used to transmit torque within the WT. These shafts not only bear the torque loads, but also the bending loads which may be time-varying, so fatigue of the shaft is an important factor to consider as well [37].

  Bearings are connected to the shafts as they carry the weight of the rotating shafts. Bearings have an important role in the drive train along and they are also used in pitch system and the yaw system [36].

  Poor lubrication, wear, pitting, deformation of the outer race and rolling elements are the main causes for failures [ref]. The shafts experience problems operating at critical speeds and at some turning speeds, shafts have resonating frequencies which can give rise to vibrations. Due to the weight, the replacements of the drive train system is a complicated procedure and requires large cranes to lift them up and down the nacelle [37].

- *Generator*
  The generator within a WT converts the mechanical rotation energy from the gearbox to electrical energy. The generator is supplied with the mechanical power (torque) from the WT rotor. The most common type of generator used in todays WTs are induction generator also known as an asynchronous generator. Modern WT with variable speeds uses such a generator which allows the varying of rotor speed with a within a wide speed range. This reduces the power fluctuations in the power grid

system as well as the loads on vital parts of the turbine [40]. The generator needs protection from water, dust and other foreign particles and only a few components are exposed to electrical and physical stress. The windings in the rotor and stator are sensitive to high currents leading to higher temperatures which can wear down the windings eventually failing them. To replace such worn-out windings, the entire generator needs to be taken out to carry out the repair. The generator bearings and fans are subjected to various mechanical wear and have to be replaced from time to time [36].

- *Yaw System*
  The rotor-nacelle assembly is placed on the yaw system which puts the assembly in an effective position against the wind. A rotating nacelle requires a yaw bearing supporting the nacelle load. The circumference of the bearing has gear teeth connected to the yaw gear which is driven by electrical motors [36] [37]. The major causes of failure of a yaw system include bearing failures, pinion and bull gear teeth pitting, yaw brake failure, pinion and bull gear teeth wear-out [29]. Yaw breaks are installed to hold the nacelle in position when the WT is not running, this can reduce the wear on the yaw system.

- *Mechanical Brakes*
  Mechanical brakes in a WT are used for mechanical braking when there is no power production and also for emergency braking. The system consists of brake discs, brake pads and callipers [41]. A mechanical brake can be located along the drive train. Excessive wear on brake linings which are caused due to emergency braking can cause brake failures and even fire [29].

- *Hydraulics*
  The hydraulic system is used to operate mechanical braking system, yaw system and the pitching system. It also operates the onboard cranes and locking systems for canopies and spinners in large WTs. The hydraulic system consists of pumps, drives, oil tanks, filters and pressure valves. The hydraulic oil in the system puts pressure on the pistons in hydraulic cylinders to move them. The system ensures that the pressure is applied when the WT is in operation and the pressure is released when it stops. A pressure sensitive valve is used to control the hydraulic pressure at a safer level.

  Hydraulic system failure are often a result of hydraulic fluid contamination, wrong oil viscosity, premature cylinder failures due to the high hydraulic fluid temperatures, hydraulic valve failure due to cavitation, faulty circuit protection devices and seal failure [29]. Most of these faults can be repaired within the nacelle itself or after the faulty parts have been exchanged [37].

- *Electrical System*
  The electrical system of the WT consists of many more parts than the generator. It consists of power converters, transformers and auxiliary electrical equipment [36] [37]. Power converters are devices that change the electrical power from one form to another. All the electrical parts can fail due to short-circuit and the magnitude of the damage is from time-to-time and these parts are mostly replaced when damaged. A transformer is a crucial component in nearly all AC power systems. It changes the

voltage of a current. The largest, main transformer in a WT is used to change the voltage of the generated power into the voltage used in internal distribution network. There are several reasons for the failure of a transformer among which are the deterioration of the insulation caused by increased heat acidity and oxidation [36]. Because of their failure modes, transformers can rarely be repaired.

Power cables and slip rings can easily be worn out. Slip rings are rotating electrical contacts used between the generator and the converter. There are many circuit breakers and fuses which are opened when the current gets too strong. Fuses need to be replaced when used for a long time and the circuit breakers need to be reset after switched on or off.

- *Sensors*
  Sensors mounted at various places on the Wt provide various data like speeds from the wind, rotor and generator, temperatures at various locations and components in a WT, electrical characteristics and various other parameters. Sensors on the outside measuring wind speed and direction often tend to fail.

- *Control System*
  Control system of a WT ensures a good, safe and reliable power production. The two main functions of the control system are: to monitor item functionality and to operate the WT. The system comprises of various hardware and software components that decide on what actions are to be taken based on the information from the sensors. The system can be damaged due to the failure of any circuit boards. If the damage is small, the boards are repaired or else they are discarded [36] [37].

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