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Development of Offshore Wind Operational Expenditure Model and Investigation of Optimum Operation and Maintenance Fleet

by

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Abstract

Offshore wind turbine technology is moving forward as an alternative to the fossil fuelled power production. However, there are a number of challenges in further offshore areas; wind turbines are subject to loads that are not often experienced onshore and more importantly challenging wind and wave conditions limit the operability and accessibility of the vessels needed to access offshore wind farms. Therefore, operating further from shore increases the logistic challenges of offshore wind operation and maintenance (O&M) activities. In contrast with the prospects, operational expenditure (OPEX) of the offshore wind farms has been increasing, reflecting greater risk for potential investors and current operators. As the power generation capacity improves constantly, advanced logistics planning of O&M activities, which supports the developers in achieving reduced downtime, optimised availability and maximised revenue, has gained vital importance.

In order to sustain the competitiveness of the offshore wind industry against other renewable energy sources, the cost of offshore wind needs to come down to today's onshore cost. This cost reduction target can be achieved through improving the offshore related operations, which contribute the most to the OPEX of the offshore wind farms. Available vessels in the market and the variety of benefits & drawbacks of different vessel chartering strategies have to be considered in the O&M planning. In this research, an offshore wind operation and maintenance expenditure model has been developed. A time domain Monte-Carlo simulation approach is implemented, which includes analyses of environmental conditions (wind speed, wave height, and wave period), operational analyses of transportation systems, investigation of failures (type and frequency), and simulation of repairs. The model enables the quantification of the influence of cost drivers and provide an improved understanding about the key aspects associated with the operational decisions.

The results of this research can assist offshore wind farm operators in developing mid-term/long-term O&M plans. Through this extensive study, it is concluded that O&M related costs can be reduced significantly while availability and productivity of the turbines can be increased by selecting correct O&M fleet in terms of size and vessel capabilities.

1 Introduction

1.1 Chapter outline

In this Chapter, the background information for the initiation of the thesis is described. Initially, the thesis layout and dissemination activities are presented following with a brief introduction to the offshore wind industry. Then, the challenges in the offshore wind operation and maintenance activities are presented. This chapter is finalised by the chapter summary.

1.2 The background of the offshore wind industry

The commercialisation of wind power started with the very first onshore wind farm installations in the USA by 1970s. The main intention of moving to renewable energy was searching for an alternative source of energy in case of a major oil crisis as in 1973. In 1980s, onshore wind market continued its development in the USA, especially with the support of the governmental incentives (Kaldellis and Zafirakis, 2012). In the 1990s, the support schemes in Europe and India, which were mainly based on fix feed-in tariffs and tax deduction for renewable power generation led to a fast increase of wind turbine installations in other regions in the world (Ackermann and Söder, 2002).

The potential risk of limited installation area due to high population density in the central Europe, especially in Germany, Denmark, Netherlands and the UK, directed European countries to offshore installations. The availability of larger areas (almost unlimited compared to onshore areas) was not the only reason for moving to offshore. There was a great potential to improve the effectiveness of the turbines. In this respect, Figure 1 shows the comparison of capacity factor levels in onshore and offshore location in the EU. The capacity factor, which is defined as the ratio of average power production of a turbine to its rated capacity, is generally used to evaluate the performance of the turbines (Abed and El-Mallah, 1997, Chang *et al.*, 2014). By installing the turbines to offshore locations, the capacity factor levels, which are generally around 25% in onshore locations, can be increased to 35% and beyond. Denmark, Germany, Netherlands and the UK are the top four counties that can benefit from the power production increase in offshore environment.

These advantages in offshore led to a real application of offshore wind turbines for more than a decade after the onshore wind farm installations; the first offshore wind farm project, which was developed by DONG Energy, started its operational life by 1991, 2.5 km off the Danish coast at Vindeby (EWEA, 2011b). The Vindeby Offshore Wind Farm consists of 11 450 Kilowatt (KW) turbines with total capacity of 4.95 Megawatt (MW). After this first application, absence of limitations associated with visual impact and noise, higher wind speeds, and the lower turbulence levels in the offshore environment encouraged operators to invest more in offshore wind farms. A special case for Europe is the fact that water depths increase gradually with distance from shore (Matthies and Garrad, 1995); therefore it is possible to capture stronger winds by keeping the turbine installation costs at optimum level. Currently, 95% of the global operational offshore wind installations are still located in European waters, the remaining 5% are commissioned in China and Japan (E.ON Climate & Renewables, 2011). Considering the high density of applications in EU, the following chapters are focused on the development of offshore wind in EU waters.

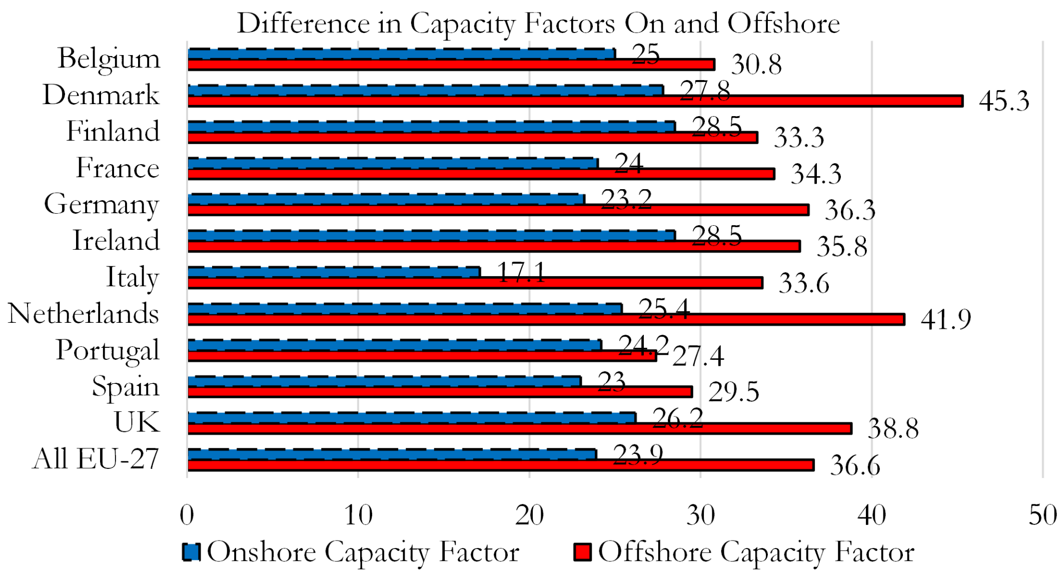


Figure 1: Differences in onshore and offshore capacity factors in the EUadapted from WindPower Offshore (2011)

1.2.1 Recent developments in total power production capacity

Offshore wind has a crucial role in Europe's safe and secure energy supply strategy, which is intended to be less dependent on fossil fuels. In this respect, Figure 2 and Figure 3 are the graphical illustrations of how the offshore wind capacity has grown in the EU waters. The offshore wind industry has seen a rapid growth in the recent years with less than 100 MW annually installed capacity in 2000s to almost 1 Gigawatt (GW) by 2010s (Figure 2). As shown in Figure 3, there is now just over 8.0 GW (annually 16 terawatt-hours, equivalent to annual electricity consumption of 4 million households) installed offshore wind capacity, which has been achieved by significant commitment for the last 5-6 years; in addition, there is 120.6 GW onshore wind capacity is available in the EU (EWEA, 2015b). However, if Europe still aims to achieve the cumulative target of 43.0 GW offshore wind capacity by 2020, an average of 7.0 GW should be installed every year for the next 5 years. In this scenario, it was expected that the UK (18.0 GW), Germany (10.0 GW) and France (6.0 GW) would contribute towards 34.0 GW. This target appears to be extremely ambitious, especially for the UK, considering the fact that the UK needs to build projects equivalent to 23 London Arrays (630 MW project capacity). The forecasts show that it is unlikely that the project capacity of Germany and France will go beyond 8.0 GW and 2.0 GW by 2020, respectively (WindPower Offshore, 2013). In addition to the increase in the number of installations and total capacity of the offshore wind market, the average size of the wind farms is also increased from 100 MW to 400 MW in the last 5 years (Figure 4). In this period, both average number of turbines in project and the power production capacity of the turbines are boosted.

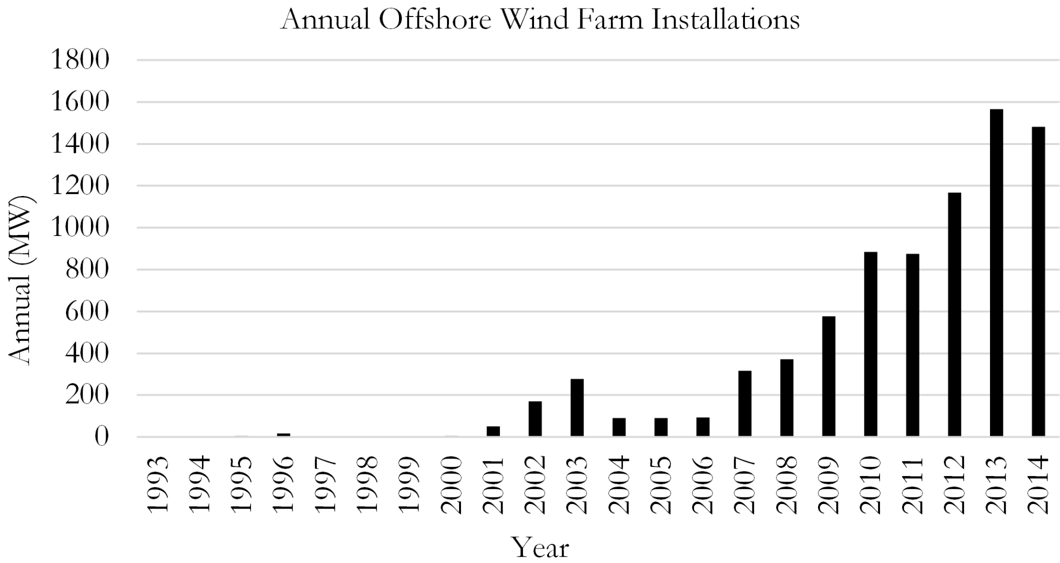


Figure 2: Annual total offshore wind farm installations in the EU(EWEA, 2015b)

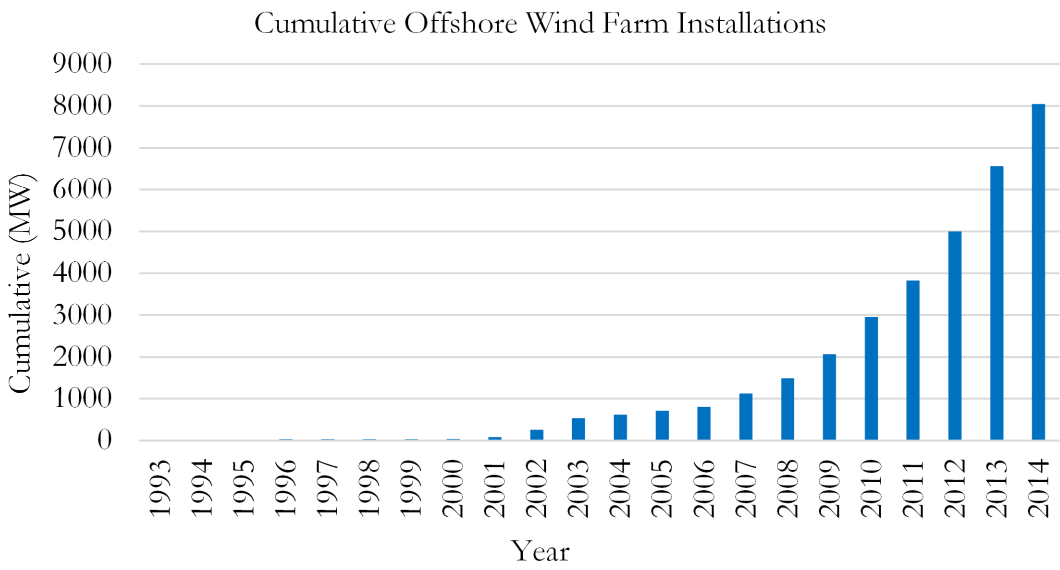


Figure 3: Cumulative total offshore wind farm installations in the EU(EWEA, 2015b)

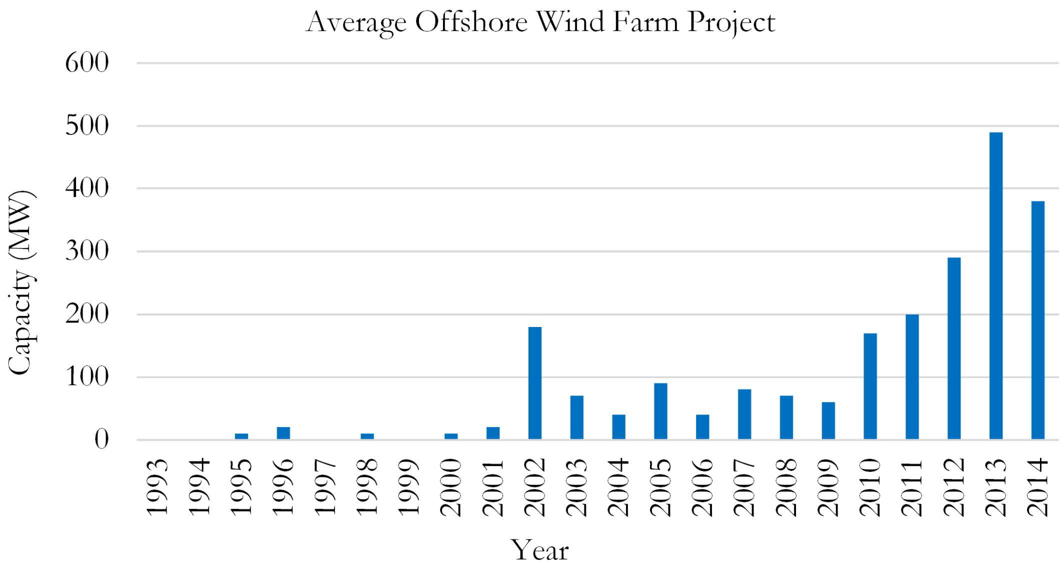


Figure 4: Average capacity of an offshore wind farm project in the EU(EWEA, 2014)

1.2.2 Recent developments in individual turbine capacity and size

Since the installation of the Vindeby offshore wind farm, power production capacity, rotor diameter and tower height of the offshore applications have been continuously increasing (Henderson *et al.*, 2003). By the time, offshore wind turbines have evolved from the earlier "marinised" versions of land-based models towards dedicated offshore turbines (IEA, 2013). The need to exploit higher winds at higher altitudes, maximise area exploitation, and minimise installation and operational costs per unit power production were the main drivers behind this continuous trend.

In this respect, Figure 5 demonstrates the development in the average turbine size within the last 20 years. In the early stages, the average turbine capacity remained below 1.0 MW; it has increased to 2.0 MW and beyond after 2000s. Currently, the average turbine size just below 4.0 MW, this is mainly due to the market domination of the Siemens 3.6 MW model (EWEA, 2014), which is followed by Vestas V90 3.0 MW model (Kaiser and Snyder, 2012). Although they are still in testing stage and not commercially viable yet, there are turbines developed by major players in the offshore wind sector such as Vestas, Siemens and Alstom with 7.5-8.0 MW power production capacity. The blades of these turbines are up to 90 m long and hub height are over 110m. As an example for mega turbines, Samsung's S7.0 171 7.0 MW turbine have been tested in Fife Energy Park in Scotland since 2013. The full scale prototype installation stage and the size of its blades are demonstrated in Figure 6.

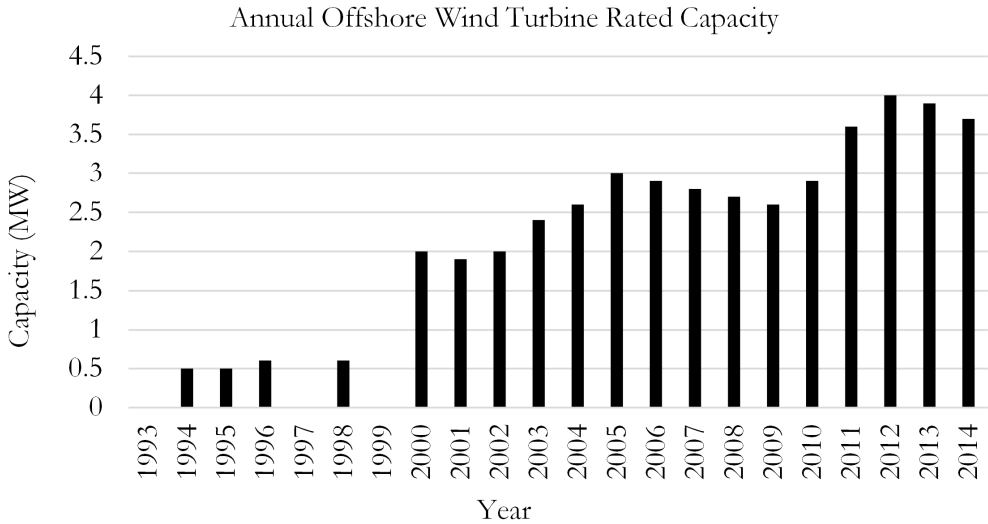


Figure 5: Average turbine rated capacity in the EU(EWEA, 2014)

Figure 6: Samsung's S7.0 171 7.0 MW turbine (SSP Technology, 2013)

1.2.3 Recent developments in water depth and distance to shore

Figure 7 shows the average water depth and distance to shore of operating (online), under construction and consented offshore wind farm projects. In this figure, the size of the circles indicates the size of the projects. It can clearly be seen that both distance to shore and water depths are increasing, especially for the consented projects. At the end of 2014, the average water depth of operating offshore wind farms was 22.4 m (12.0 m in 2009, 17.4 m in 2010, 22.8 m in 2011, 22.0 m in 2012, 20 m in 2013) and the average distance to shore was 32.9 km (14.4 km in 2009, 27.1 km in 2010, 23.4 km in 2011, 29.0 km in 2012, 30.0 km in 2013) (EWEA, 2010, EWEA, 2011a, EWEA, 2012, EWEA, 2013, EWEA, 2014, EWEA, 2015a). So, the average water depth is almost doubled in number and the average distance increased more than two times compared to the values in 2009. Considering the project under construction, consented and planned, the average water depth and distance to shore are estimated to increase.

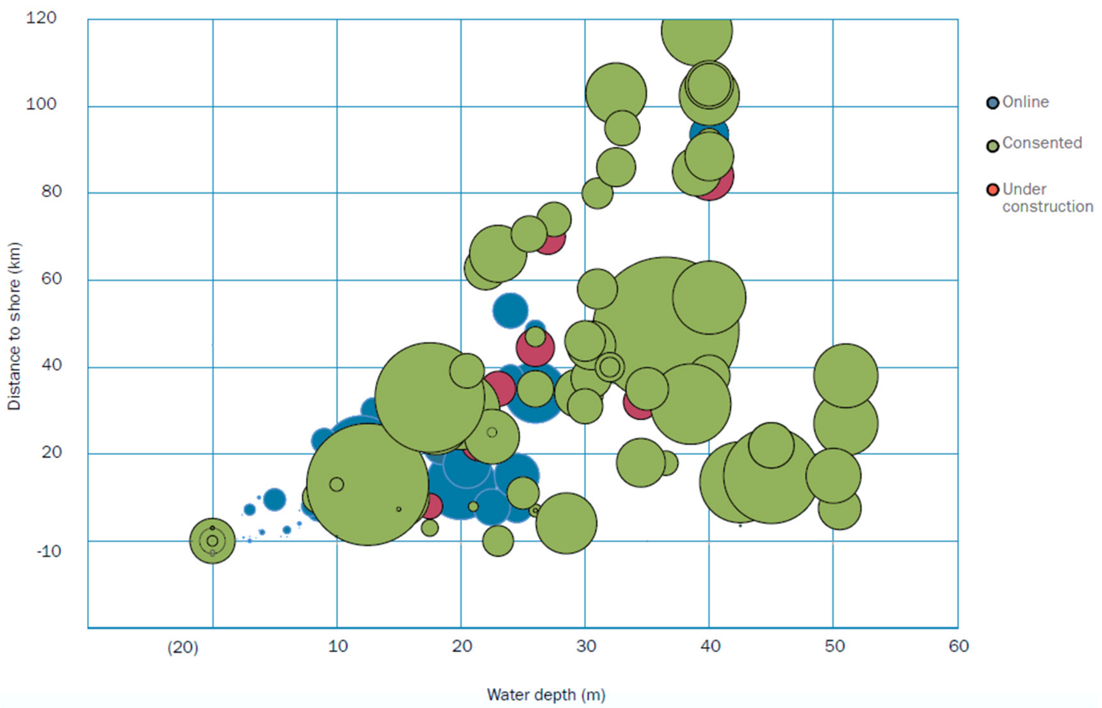


Figure 7: Offshore wind farm average water depths and distance to shore in the EU(EWEA, 2015a)

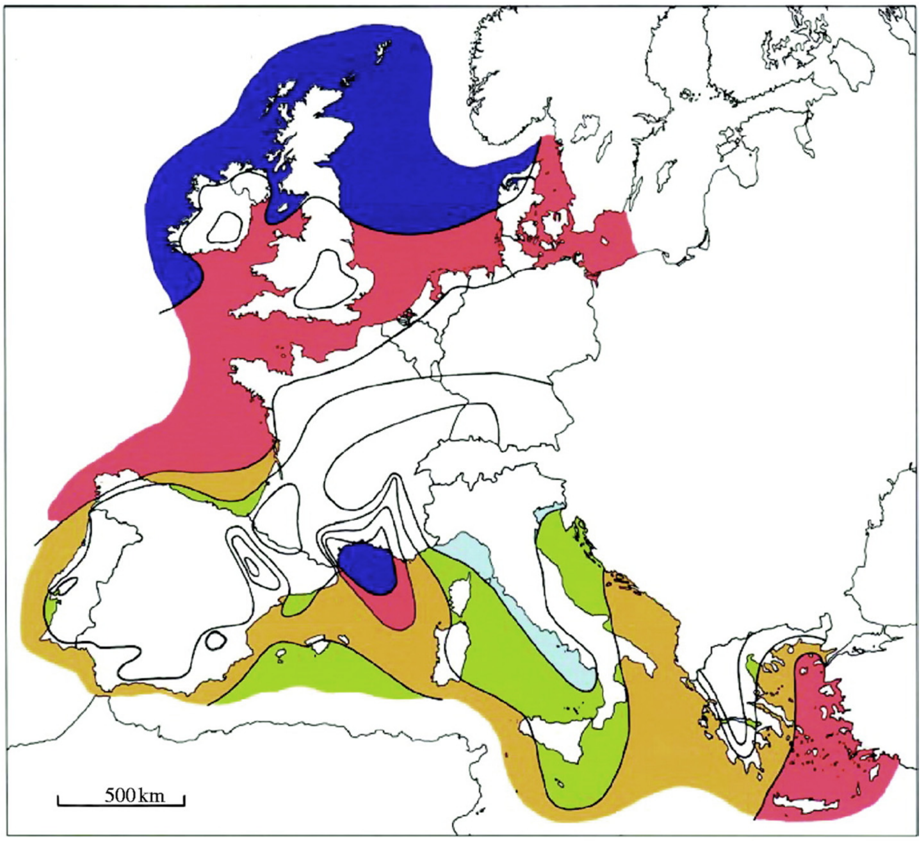
1.3 Country statistics

By the end of 2014, there are 2488 offshore wind turbines installed and grid connected, with a cumulative total of 8.0 GW in 74 offshore wind farms in 11 different European countries (EWEA, 2015a). It is expected that 15,000 turbines will be operating in the EU waters by 2030 (TPWind Advisory Council, 2015). The UK, Denmark and Germany have the highest share within the overall turbine numbers and total installed capacity (Table 1). The UK dominates the offshore market in installed number of turbines and total installed capacity. 52% of the offshore wind turbines and 55% of the total installed capacity are located in the UK waters. The main drivers behind this development are the very high wind resources, which are the best in Europe as shown in Figure 8 and the government incentives, which intend to diversify the energy portfolio of the suppliers and decrease the carbon emissions (Dinwoodie, 2014). The Renewables Obligation, which was introduced in 2002 by the UK government, places an obligation on energy suppliers by forcing them to pay financial penalties if they do not present sufficient number of Renewables Obligation Certificates (ROCs) as a proportion of the amount of electricity which they supply to the customers (Department of Energy & Climate Change, 2014). There are also similar incentives announced by Germany such as German Renewable Energies Act (Erneuerbare-Energien-Gesetz or EEG) and German Energy Industry Act (Energiewirtschaftsgesetz or EnWG).

In the UK, the first offshore wind farm developments were commenced by 2000s with the development of the Round 1 sites. The offshore wind development accelerated by the Round 2 sites. The sector has developed with a series of licensing 'Rounds' co-ordinated by the Crown Estate, the landlord and owner of the seabed. Round 1 was launched in 2001 and is now almost complete. It involved 18 sites in England and Wales, and added a potential capacity of 1.5GW. In 2003, the much larger Round 2 was issued, located further offshore and in deeper waters. It was formed of the three strategic areas; Greater Wash, Greater Thames and Irish Sea and when complete Round 2 will add another 7GW of capacity. The UK Round 1 and 2 sites are distributed within 12 nautical miles of shore at depths of up to 35m and total power production capacity is 8.0 GW (Carbon Trust, 2008). In June 2008, the Crown Estate announced the Round 3 leasing process to provide additional 25.0 GW, which are intended to include much larger turbines, higher power production capacity, installed in deeper waters and longer distances from shore. The largest, Dogger Bank, has the potential to generate up to 13GW of power and is one of the largest energy projects anywhere in the world.

Table 1: Country statistics (EWEA, 2015a)

Name	Number of farms	Number of turbines	Proportion in number	Capacity (MW)	Proportion in capacity
Belgium	5	182	7.32%	712	8.85%
Germany	16	258	10.37%	1049.9	13.05%
Denmark	12	513	20.62%	1271	15.80%
Spain	1	1	0.04%	5	0.06%
Finland	2	9	0.36%	26	0.32%
Ireland	1	7	0.28%	25	0.31%
Netherlands	5	124	4.98%	247	3.07%
Norway	1	1	0.04%	2	0.02%
Portugal	1	1	0.04%	2	0.02%
Sweden	6	91	3.66%	212	2.64%
UK	24	1301	52.29%	4494.4	55.86%
Total	74	2488	100.00 %	8045.3	100.00%

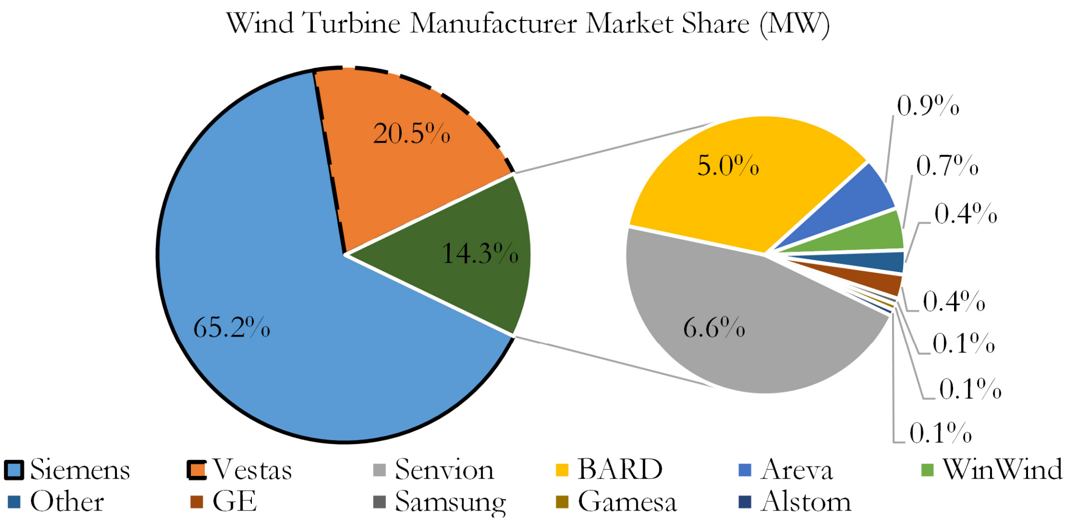


wind resources over open sea (more than 10km offshore) for five standard heights										
	10m		25m		50m		100m		200m	
	$m s^{-1}$	$W m^{-2}$	$m s^{-1}$	$W m^{-2}$	$m s^{-1}$	$W m^{-2}$	$m s^{-1}$	$W m^{-2}$	$m s^{-1}$	$W m^{-2}$
	>8.0	>600	>8.5	>700	>9.0	>800	>10.0	>1100	>11.0	>1500
	7.0–8.0	350–600	7.5–8.5	450–700	8.0–9.0	600–800	8.5–10.0	650–1100	9.5–11.0	900–1500
	6.0–7.0	250–300	6.5–7.5	300–450	7.0–8.0	400–600	7.5 – 8.5	450 – 650	8.0 – 9.5	600 – 900
	4.5–6.0	100–250	5.0–6.5	150–300	5.5–7.0	200–400	6.0 – 7.5	250 – 450	6.5 – 8.0	300 – 600
	<4.5	<100	<5.0	<150	<5.5	<200	<6.0	<250	<6.5	<300

Figure 8: Europe offshore wind map(Troen and Petersen, 1989)

1.4 Wind turbine manufacturers

Figure 9 shows the market share of wind turbine manufacturers in terms of total capacity and number of turbines installed. In both categories, Siemens (Germany) appears to be the market leader by 65%. The cost and associated risks involved in the development stage of the turbines and difficulty of getting accepted by the operators mainly restricted the proliferation of other manufacturers (Dinwoodie, 2014). The onshore experience was also important for Siemens to increase their share in the offshore wind market. Siemens is followed by Vestas (Denmark), which has a 20.5% and 25% share in total capacity and number of turbines, respectively. The remaining is shared by Senvion (Germany), BARD (Germany), Areva (French), WinWind (Finland), GE (USA), Samsung (South Korea), Gamesa (Spain), Alstom (France) and other small companies.



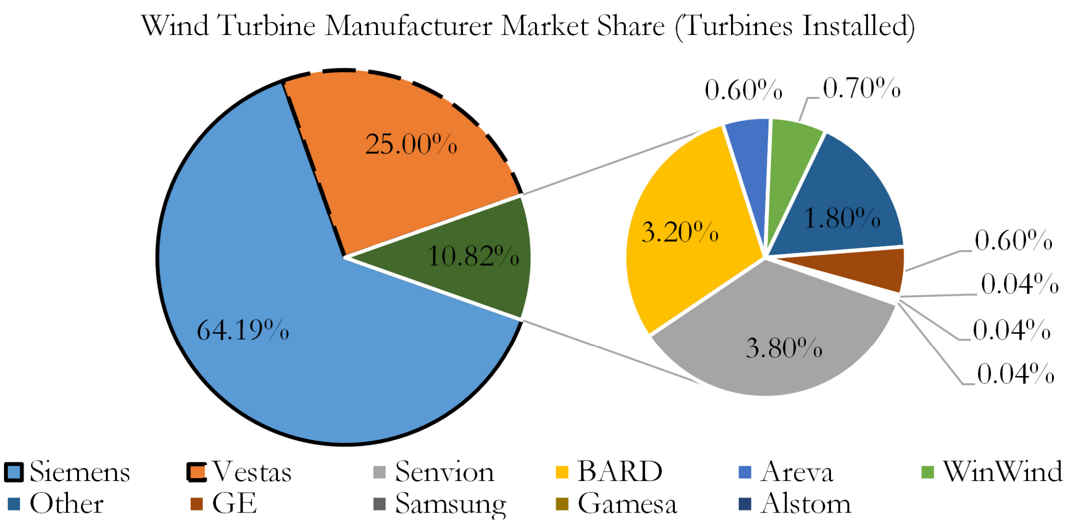


Figure 9: Market share of the offshore wind turbine manufacturers(EWEA, 2015a)

1.5 The economics of offshore wind energy

Despite all the advantages, harvesting energy from offshore wind is still much more expensive than power generation from onshore wind farms. Taking into account the UK with the greatest operating capacity in its waters, offshore wind Levelised Cost of Energy (LCOE) reached £140/MWh in 2011 (PricewaterhouseCoopers, 2012, The Crown Estate, 2012). Offshore wind capacity is still around 50% more expensive than onshore wind; however, the energy production indicator for onshore installations is normally around 2,000-2,500 full load hours per year, while for a typical offshore installation, it reaches up to 4,000 full load hours per year (EWEA, 2009, Hahn and Gilman, 2013). The LCOE of onshore is £100/MWh (IRENA, 2012). It is also important to compare offshore wind LCOE with other renewable energy sources to identify the competitors of offshore wind. The LCOE of utility-scale solar photovoltaic ranges between £70/MWh and £190/MWh depending on the scale of the project; similarly concentrating solar power LCOE is around £110/MWh (IRENA, 2015c). Hydropower projects have an average of £30/MWh LCOE (IRENA, 2015b). LCOE of biomass is slightly higher than hydropower, in the region of £50/MWh (IRENA, 2015a). These figures show that the LCOE of offshore wind is higher than other renewable energy sources and therefore the cost of offshore wind needs to be reduced in order to improve the competitiveness of the sector.

In practice, LCOE is the most common term to describe the costs. LCOE is defined as the sum of discounted lifetime generation costs (£) divided by the sum of discounted lifetime electricity output (MWh). In this respect, the generation costs comprise of all capital, operating, and decommissioning costs incurred over the lifetime of the project. More complicated foundations, longer electrical networks, installation and maintenance that are dependent on vessels, and harsher wind and wave conditions that limit the operability of vessels and subsequently the accessibility of offshore wind farms for installation and maintenance activities can be considered the major factors that escalate the cost of offshore wind projects.

The two major contributors to LCOE are capital expenditure (CAPEX) and operational expenditure (OPEX). In a generic principle, two thirds of LCOE is spent on CAPEX and the remaining one third is spent on OPEX (Figure 10). Turbine supply, Balance of Plant (BOP) supply and installation costs have the highest proportion within overall CAPEX.

The breakdown of each major contributor can be found in Figure 11. Turbine supply cost involves manufacturing and system level assembling costs. Balance of plant comprises of export and inter-array cables, turbine foundations, and offshore and onshore substations. Installation includes transportation and assembly of both turbine and balance of plant items. Project costs consist of wind farm design, environmental surveys, project management, site investigation and many other tasks. O&M essentially includes day-to-day operations, spares, consumables, condition monitoring, vessels, technicians, grid use charges, rent to Crown Estate and insurance. In the UK, the seabed (up to 12 nautical miles) is owned by the Crown and managed by the Crown Estate; therefore, energy suppliers pay a rental fee to run the cables along the seabed.

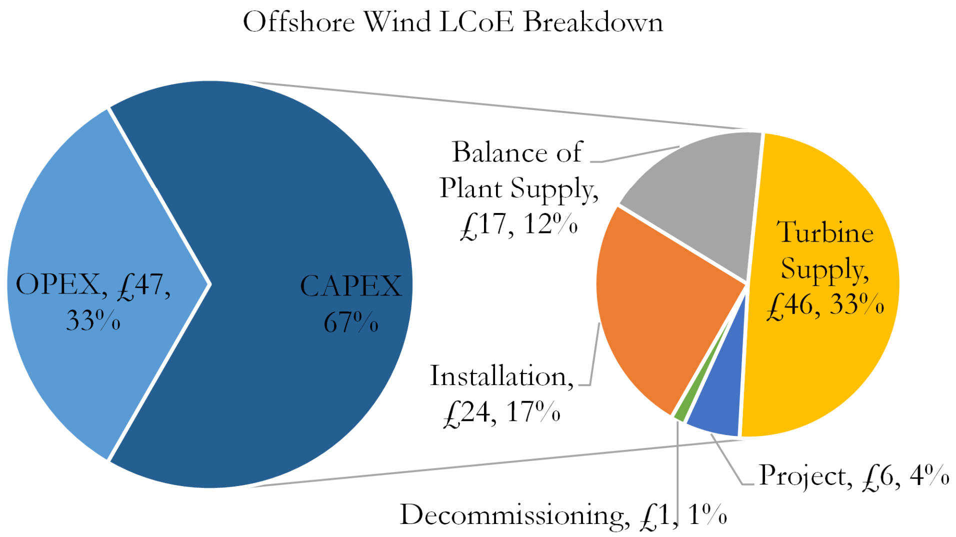


Figure 10: Offshore wind LCOE breakdown(Roberts *et al.*, 2014)

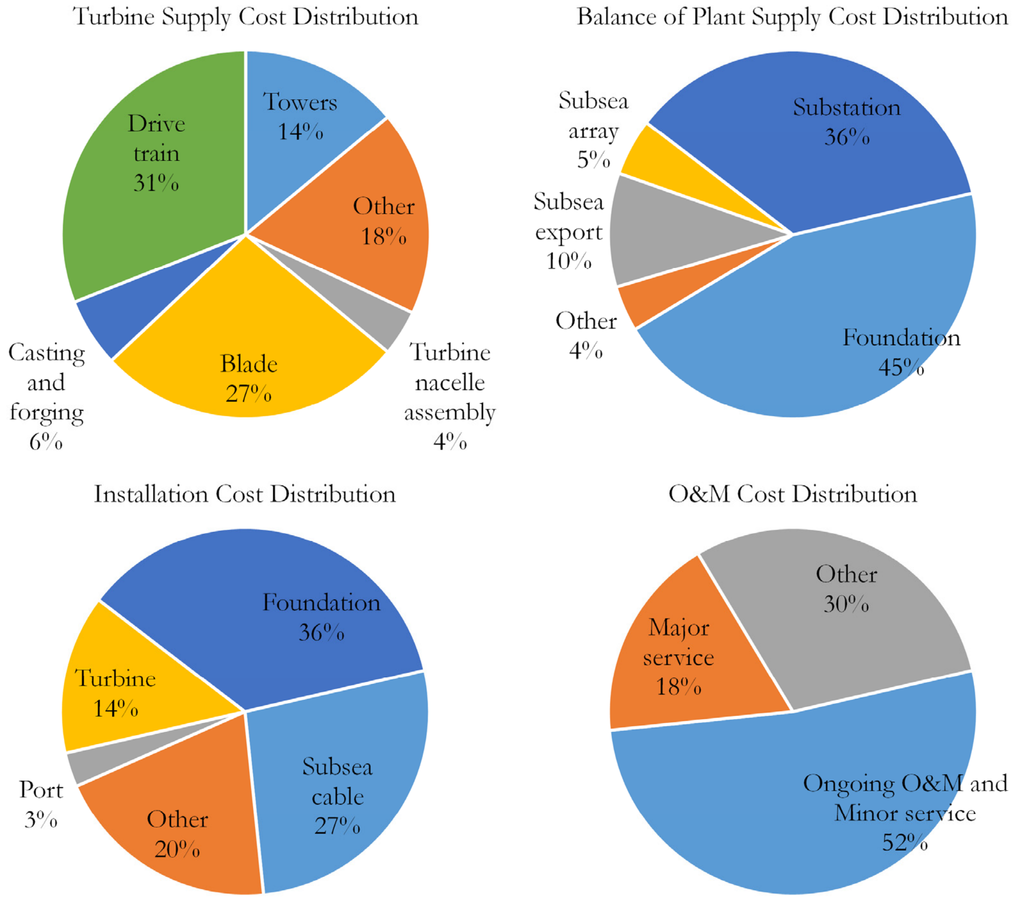


Figure 11: Distribution of major cost aspects(BVG Associates, 2013)

1.6 Challenges and issues in offshore wind operation and maintenance sector

In this section the challenges in offshore wind O&M are listed in order to diagnose the core issues which increase the costs and eventually decrease the competitiveness of the industry. These issues are also important for the identification of the research direction.

- Availability is the percentage of time that an individual wind turbine or wind farm is available to generate electricity expressed as a percentage of the theoretical maximum. Although onshore wind farms can present 98% availability (Van Bussel and Zaaijer, 2001), offshore wind farm availability can be as low as 63-65% (Carbon Trust, 2008). Such a lower availability results in unexpected and significant revenue loss.

- Due to the immaturity of the market, the component and spare parts supply can be an issue, particularly for the major components such as generator, gearbox, blade and tower. Since a component standardisation is not achieved yet, operators are under risk of long lead times (RenewableUK, 2012).

- Challenging climate conditions limit the accessibility to the offshore sites. With the current operational limitations (1.5 m significant wave height), offshore sites can be accessed 200 days in a year (Carbon Trust, 2012). For onshore examples, the accessibility is generally close to 100% (Karyotakis, 2011). By the increasing distance from shore, the accessibility should be expected to be lower, unless offshore-based platforms are considered.

- The vessels utilised for the major component replacements generally need considerably long lead times (mobilisation time), which typically vary between two and six months; however, there are examples of longer waiting times in some circumstances (The Crown Estate, 2014). The site investigation and documentation takes around 3 months, additionally 2 months for the sourcing the vessel from spot market and charter negotiations, and 2 weeks for the vessel mobilisation of the vessel and deck preparation (DBB Jack-up, 2014).

- It should not be forgotten that O&M ports are also a part of O&M planning. Their capacity, limitations and particularly distance to offshore wind farms can play a key role in decision stage. The Greater Gabbard site can be a particular example, since its average distance to shore is 20 nm; however, the distance between the O&M port and the site is 40 nm (The Crown Estate, 2013).

- O&M activities are dependent on the vessels. For the failures of large and heavy components, specialised vessels, which the number of these vessels is significantly low, are required to be utilised. Considering the excessive charter rates, disorganised O&M activities results in major cost increase.

- From cost point of view, it is also very important to keep the turbines functional. Due to higher wind speeds, the potential revenue loss in offshore sites can reach up to £30,000 by keeping a turbine off a week, while an onshore turbine failure can result in £5,000 revenue loss in the same period (Dinwoodie, 2014).

- Unlike offshore oil and gas platforms, turbines are unmanned structures, for which technicians are required to be transported for any kind of planned or unplanned activity. In addition, teams of 2-5 technicians can be required on multiple wind turbines in a single working day, in contrast with 20+ technicians stationed on one large oil or gas installation (GL Garrad Hassan, 2013).

- The availability of the trained personnel is also another major issue in offshore wind, considering the rapid sector expansion, the demand is more than ever to fill (Marsh, 2007).

- In practice, most wind farms are covered with up to a five-year warranty and maintenance contract. In this period, Original Equipment Manufacturers (OEMs) are responsible for the turbine O&M and technician supply; on the other side, operators are responsible for the technician access and BOP repairs. As the warranties for the Round 1 and the early Round 2 wind farms, which were installed in 2010 or before, are due to expire soon in the UK (Hashem, 2014), financial and operational risks will rest with the operators. It should be highlighted that major and expensive components can start to fail, because the minimum O&M requirements are fulfilled by OEMs over the warranty period.

- The monopoly situation in the offshore wind turbine manufacturing industry strengthens OEM's hand in the decision stage of the O&M contracts; they can have the rights to share limited information with operators. Since, O&M is carried out by OEMs over the warranty period, operators cannot be very keen to take risk of in-house turbine O&M, which they have limited information.

- The number of research activities, which help industry to develop, optimise operations and minimise costs, is limited for offshore wind O&M. Figure 12 shows the number of publications about 'offshore oil and gas', 'offshore wind', 'offshore wind maintenance', 'offshore wind maintenance vessel' in the major databases such as ScienceDirect, Engineering Village, Web of Science and Institute of Electrical and Electronics Engineers (IEEE). It can be seen that although decent effort has been spent on offshore oil and gas and offshore wind topics, O&M and especially vessel associated aspects are not investigated thoroughly. Considering the fact that O&M vessels play a key role in the operations, their influence should be investigated in depth.

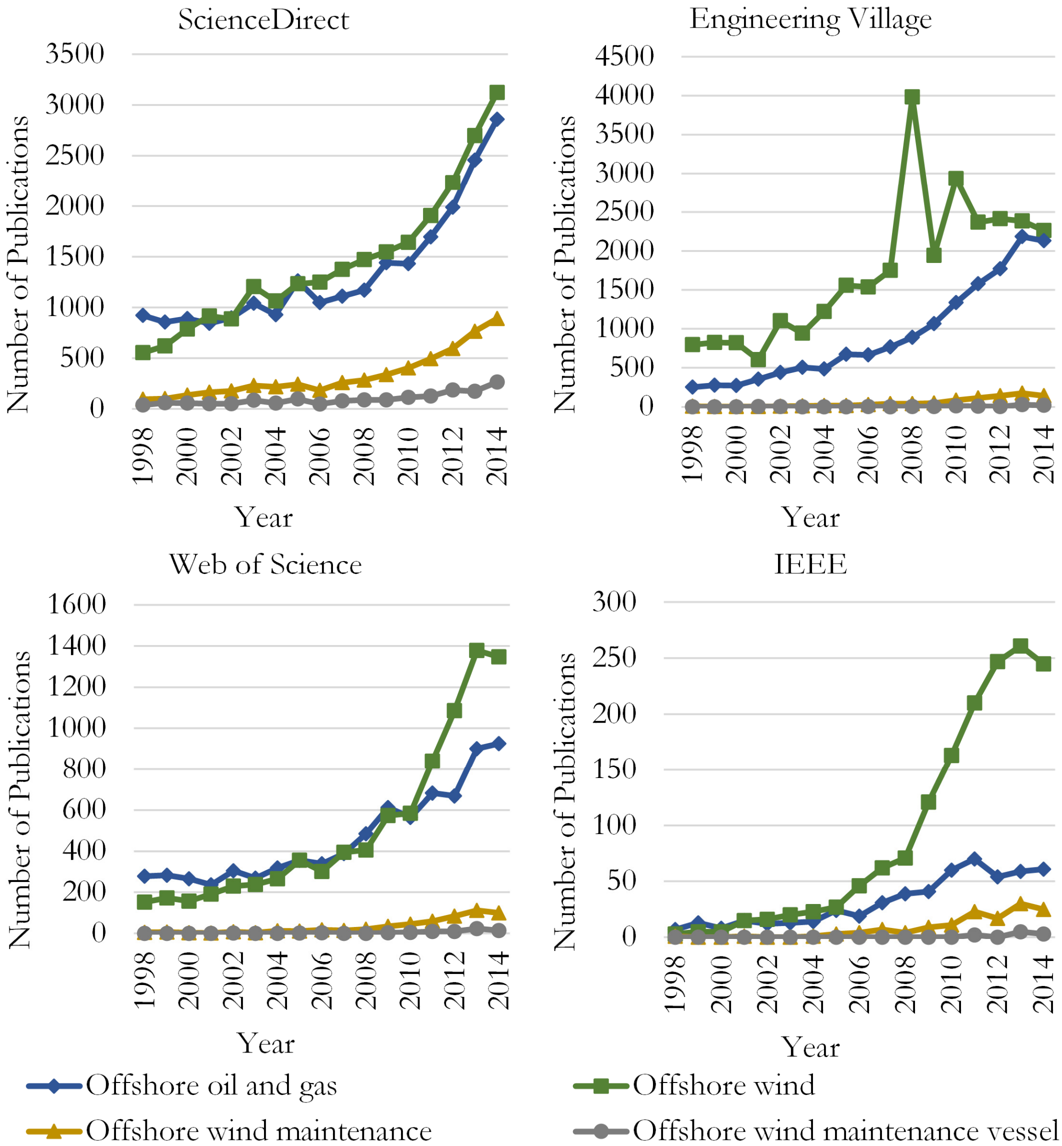


Figure 12: Number of publications about offshore subjects

1.7 Thesis layout

Each chapter of the thesis starts with a chapter outline, which suggests what the reader can expect to learn from the chapter, and provide the reader with a brief introductory information. At the end of each chapter, there is a summary of achievements including some key messages emerging. The thesis is structured in nine chapters, which are summarised below:

Chapter 1. Introduction

This chapter sets out the wider context for the thesis, introduces the topic and key concepts and outlines the methodological approach and structure.

Chapter 2. Aim and Objectives

This chapter introduces the main aim of the thesis, the industrial problem description and the motivation for this research study. The objectives present the major research challenges achievements that are intended to be tackled in order to achieve the main aim of the thesis.

Chapter 3. Literature Review

The literature review chapter intends to clarify the technical, operational and financial challenges in the current offshore O&M. This section presents a critical and comprehensive review of the literature about offshore wind farm O&M activities varying from the vessel associated aspects to the turbine failures. A detailed review of offshore wind O&M modelling techniques is covered and the research gaps in the existing literature are identified.

Chapter 4. Methodology and Modelling

Considering the identified gaps in the existing literature, this chapter concentrates on the theoretical framework and explains underlying principles of the developed model. The structure, functionality and key assumptions are explained in depth. In addition, the relations and the interactions between analysis and calculation methods are demonstrated.

Chapter 5. Case Study - Investigation of Optimum O&M Fleet Usage

This section starts with the presentation of the input sections of the proposed modelling approach: climate observations, vessel pool, vessel specification, operational decisions, vessel chartering, wind farm/turbine specific attributes, and cost specific attributes. After identifying the input parameters, the analysis/calculation sections: climate generation, vessel operability and transit time calculation, failure simulation, repair simulation, power calculation, cost calculation blocks are described by synthesising the information defined in the input sections. The major results of this case study are presented and the benefits of optimising the O&M fleet and its usage are quantified.

Chapter 6. Case Study – Benefits of Mothership Concept

In this chapter, a particular focus is given to the mothership concept and its usage within the O&M fleet. A base case is established and the consequences of considering a mothership in the O&M fleet are identified.

Chapter 7. Sensitivity Analysis

The sensitivity analysis chapter presents a rigorous analysis of the operational parameters influencing the performance of offshore wind farms. A base case is established considering the initial results in the previous section and variations are implemented to the inputs. In this chapter, the key parameters are identified and their influence on the costs and power production is quantified.

Chapter 8. Discussion and Recommendations for Future Work

The discussion of the overall thesis takes place in this chapter. Furthermore, the progress of how the objectives of the thesis are achieved is explained and discussed. Recommendations for future research studies are also presented in this chapter.

Chapter 9. Conclusions

The novelty of this research study, the contributions to theory and practice are presented in this chapter. The concluding statements are provided in this chapter. The final chapter summarises the key learning points of this research.

1.8 Research outputs

The following peer reviewed journal articles, conference proceedings and industry reports/workshops have been outputs during this PhD work;

Journal publications

Dalgic, Y., Lazakis, I. & Turan, O., 2015. Investigation of Optimum Crew Transfer Vessel Fleet for Offshore Wind Farm Maintenance Operations. *Wind Engineering,* 39**,** 31-52.

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1.9 Chapter summary

In this Chapter, the thesis layout explains what is covered in each section of the thesis. Then, the background of offshore wind and the current developments in the sector are demonstrated to present the prospects and more importantly what should be taken into account in order to develop a comprehensive model. This sophisticated model can also be used for forthcoming projects. Thereafter, the challenges in the offshore wind O&M activities are presented. In the following section, a comprehensive literature review is conducted in order to identify the gaps, which are then addressed in the developed methodology.

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2 Literature review

2.1 Chapter outline

Widespread of wind farms, turbine size & capacity increase, and uncertainty in the O&M planning due to climate seasonality and offshore site characteristics have created a necessity for a comprehensive, innovative and bespoke approach, which can support operators/developers in the offshore wind O&M. This approach has to consider business specific variables and objectives in addition to major aspects such as availability and power production. In this context, a comprehensive review is needed to identify the technical, operational and financial challenges in the current onshore/offshore O&M. It is also required to categorise the aspects that influence O&M tasks and associated costs. From these, a favourable and cost-effective O&M fleet can be established. This section presents the review of the literature about offshore wind farm O&M activities varying from the vessel associated aspects to the turbine failures.

This chapter starts with the section about available O&M practices. Due to the fact that several terms are introduced to represent the same O&M tasks, an introduction to O&M is given and the most comprehensive terminology is selected. In order to have a consistent structure, the same terminology is used in the following sections. Since not all the O&M practices are applicable to the offshore wind industry, the most relevant practices are defined and existing studies are presented. Due to the fact that offshore wind industry is mainly influenced by onshore wind and offshore oil & gas industries, major multi-sectoral studies are also presented. Among these studies, it has been identified that there are available tools, by which O&M activities are modelled. It has also been identified that there are major gaps in the offshore wind O&M literature, especially in the vessel categorisation, vessel selection and fleet configuration stages. Considering these major gaps, a comprehensive review of O&M fleet selection process is introduced. It should be highlighted that fleet selection is a sophisticated process, because it is not simply a vessel selection process; instead, this process requires investigation of climate, financial and reliability aspects in addition to the vessel properties. Thereafter, the summary of this chapter is presented in the final section.

2.2 O&M practices

Before focusing on the offshore wind turbine specific O&M practices, it is important to highlight the O&M terminology in order to evaluate advanced strategies precisely. In the literature, there are different expressions in order to describe the same O&M tasks. Higgins *et al.* (2008) described O&M approaches under three main sections: breakdown, corrective and preventive. Pérez *et al.* (2010) categorised O&M approaches as preventive, predictive, corrective (fault diagnosis), corrective (inspections) and proactive. Garg and Deshmukh (2006) sub-classified into preventive maintenance, condition-based maintenance, total productive maintenance, computerised maintenance management systems, reliability centred maintenance, predictive maintenance, maintenance outsourcing, effectiveness centred maintenance, strategic maintenance management and risk-based maintenance. According to Wiggelinkhuizen *et al.* (2008), O&M tasks can be classified under preventive maintenance and corrective maintenance. In order to be consistent in the thesis, the framework introduced by Kobbacy and Murthy (2008) for the definition of O&M task formation is taken into account (Figure 13).

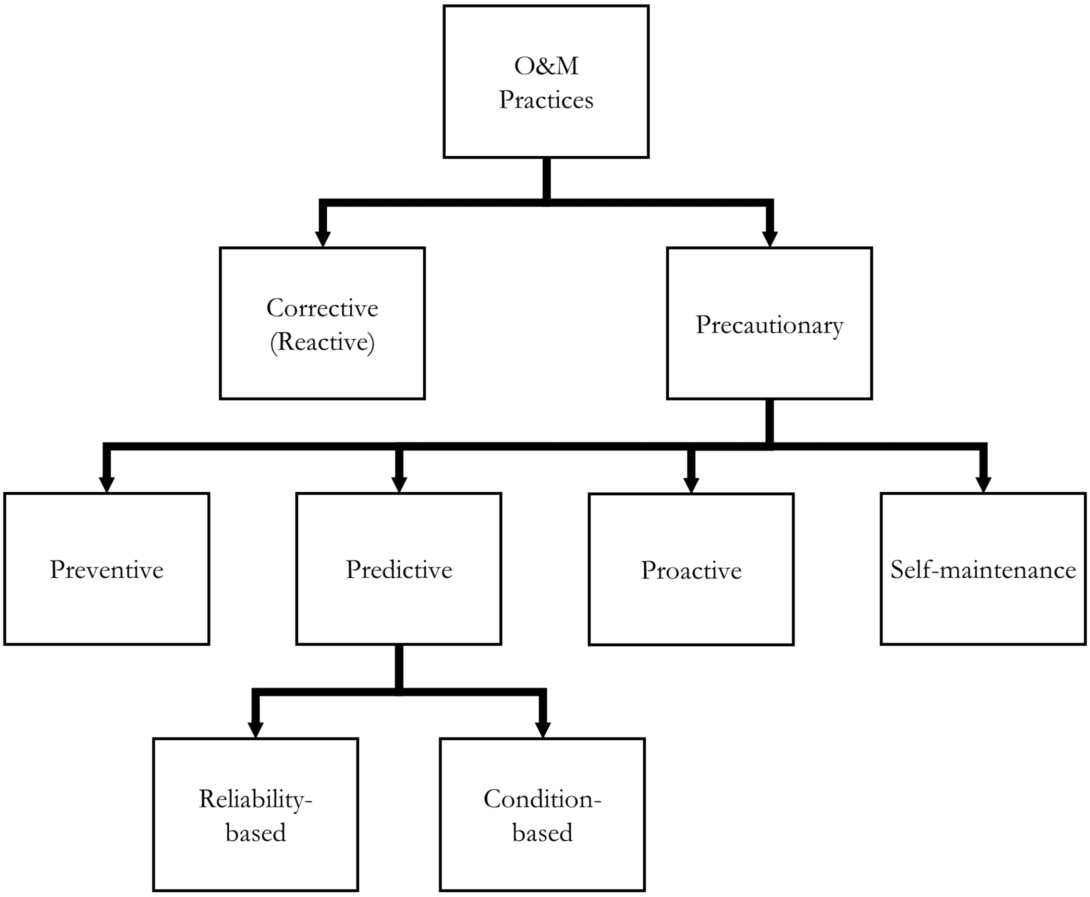

Figure 13: O&M practicesadapted from Kobbacy and Murthy (2008)

The O&M practices in Figure 13 are elaborated below in order to explain the key features and demonstrate the main differences among these O&M practices.

- *No maintenance* can be a solution, when none of the available O&M practices is appropriate to implement or decommissioning is more cost-effective than performing the O&M task.
- *Corrective maintenance* is the unplanned O&M activity after a reported failure. Longer downtime, cost implications related to equipment, labour and logistics are the most common drawbacks of the corrective maintenance. According to Higgins *et al.* (2008) corrective maintenance can cost four times more than the cost of the same repair when it is planned ahead. Therefore, minimising corrective maintenance is the key to reduce the O&M costs.
- *Preventive maintenance* requires periodic actions in order to reduce the probability of failure and prevent the degradation of equipment regardless of its condition at the inspection time. Lubrication, filter renewals are the typical examples for preventive maintenance. The main shortcoming, which operators come across, is the unnecessary repairs.
- *Predictive maintenance* aims to perform the O&M activity just before failure through analysing performance data, O&M history, operator logs and design data. Therefore, as an advanced O&M concept, predictive maintenance requires both technology and human skills. Although the cost of hardware and software increases the entire operation and O&M costs, predictive maintenance offers increased reliability, which leads operators to reduce unexpected downtime and operating costs.
- *Proactive maintenance* is a new O&M concept, which intends to analyse root cause of the failures, not just the symptoms as in the predictive maintenance. If an action is performed that prevents/fixes failures from their main sources, than it can be referred to proactive O&M, which is an enhanced form of predictive maintenance. Proactive maintenance minimises sudden stops caused by breakdowns and eventually maximises productivity.
- *Self- maintenance* is the most advanced method, which requires machines with self-monitoring, self-fault judging, self-diagnosing, repair planning, repair executing, self-learning and improvement capabilities.

Due to the fact that accessibility of onshore wind farms is relatively higher than accessibility of offshore wind farms and the issues related to onshore O&M activities are less challenging, a different approach has to be developed in order to ensure a reliable and cost effective source of power production in offshore environment. Among the generic O&M models, the most efficient method appears to be self- maintenance methodologies (Lee *et al.*, 2011). However, the immaturity of offshore wind technology compels offshore wind operators to focus on preventive and predictive concepts. Although the mainstream of the research associated with the offshore wind O&M concepts is dominated by the preventive and predictive O&M concepts, they are still not mature enough to support operators in competing with the onshore power production costs. Furthermore, the implementation of these advanced O&M approaches does not give satisfactory results for the entire offshore wind farm projects.

In the following section, the research related to O&M concepts, O&M strategies and supporting studies in the context of offshore wind turbines are presented. The examination of these studies is the essential starting point for the model development, which considers the strengths and the weaknesses of the past research. The identification and evaluation of previous studies allows the new model to cover unexplored areas, which past studies could not consider.

2.3 Existing studies associated with offshore wind O&M

At this point, it is important to highlight that *no maintenance* and *self-maintenance* approaches are outside the scope of this study. The reason behind is, *no maintenance* is not an industry standard for the offshore wind O&M, in which dramatic downtime and revenue loss can be expected. Additionally, *self-maintenance* methodologies can essentially be formed by the innovative materials and advanced computer systems, which can self-diagnose the signals and react the potential failures. However, *self-maintenance* methodologies for offshore wind industry are still in concept stage and there is no application in the sector. These approaches are also excluded in this study to focus on the most feasible and essentially, applicable methodologies. Therefore, the previous research studies, which are presented in this section, include corrective, preventive, and predictive methodologies.

In this respect, Alsyouf and El-Thalji (2008) reviewed the O&M practices for wind power systems. They pointed out that the goals and challenges identified are already achieved in other industries such as aeronautical, shipping and automotive. Therefore, there is a research need in order to apply these good practices to offshore wind turbine industry. Utne (2010) discussed the O&M strategies for deep-sea offshore wind farms and indicated that the existing models generally consider single units and single component systems. For enhanced O&M models, it is also suggested that condition based O&M have to be supported by reliability based maintenance. One of the major issues about research activities is the noticeable gap between academic research and industrial stakeholder expectations from O&M strategies; there are many theoretical models, however most of them are not applicable to industry (Utne, 2010). El-Thalji (2012) indicated that it is important to utilise models and practices, which can fit with the reality and the operating environment.

2.3.1 Corrective maintenance

Corrective maintenance is performed when any of the turbine components breaks down or fault is detected. Marquez *et al.* (2012) and Ben-Daya *et al.* (2009) believe that corrective maintenance is the most expensive methodology among all the strategies, due to potential need for immediate refurbishments and replacements. Ding and Tian (2012) proved that significant cost savings (~48%) can be achieved by harmonising preventive maintenance with current corrective maintenance methodology. Hameed *et al.* (2010), Nielsen and Sorensen (2011), Van Horenbeek *et al.* (2013) highlighted that there is a high prospect of failures occurring within large wind loads, which can cause extensive production and financial loss due to inaccessibility of the site during bad weather; therefore, corrective maintenance, in which a minor component failure can lead to severe consequential damages, can cost much more than preventive maintenance. Giebhardt *et al.* (2004) agreed that corrective maintenance reserve risks associated with extensive downtime, complicated logistics, lack of scheduling, and long delivery periods for spare parts.

Due to the nature of the operational environment and immaturity of the offshore wind industry, it is believed that corrective maintenance is unavoidable. Even in highly developed industries such as railway transportation, oil and gas, etc., corrective maintenance activities are still performed. At this stage, it is important to improve the operators' reaction capability to unexpected failures by improving O&M fleets and minimising vessel transit; thus, downtime due to failures can be minimised and power production can be maximised.

2.3.2 Preventive maintenance

Preventive maintenance is based on the expected lifecycle of the component, which is provided by the Original Equipment Manufacturers (OEM). Preventive maintenance activities include time-based turbine visits (i.e. every six months) and comprise mechanical checks of fluid levels, greasing, blot torque checks, filter changes, inspection of blades and brake pads. However, materials/equipment can deteriorate quicker than it is determined by the OEM depending on the operating environment and conditions, which increases the risk of corrective maintenance. According to Harman (2012), the operational life of a wind turbine can be undesirably less than 20 years, if preventive maintenance intervals are determined without considering site specific conditions such as low/high altitude, hot or cold weather, wet or dry weather.

A report prepared by DNV (2004) recommended that the interval of the periodical inspections of the structural and electrical systems above water should not exceed 1 year. The structures below water and the sea cables should be inspected at least every 5 years; so that the whole wind farm is inspected at least once during a period of 5 years. Fenton *et al.* (1992) recommended an inspection for the stator winding of the generator following the first year of service. The second inspection can be performed when the generator completes five years of service, unless the generator has been exposed to severe duty, abnormal operation, or other conditions known to be of concern to generator integrity.

As for preventive O&M, the main research idea is optimisation of O&M intervals. Due to the fact that specific inspection periods are determined by the OEMs, as an operator the only intervention can be analysing the provided information from different manufacturers and planning O&M intervals for the entire offshore wind farm projects. In this regard, Andrawus *et al.* (2008) succeeded in optimising the wind turbine inspection intervals. According to this study, optimal inspection intervals for gearbox and generator bearings are 3.045 and 3.349 months, respectively. Nielsen and Sorensen (2011) recommended that the inspection intervals have to be 6 months in order to keep the corrective maintenance and inspection costs in balance. Yan-ru and Hong-Shan (2010) achieved 25% decrease through optimising the preventive maintenance intervals for wind turbines. Eunshin *et al.* (2010) developed an optimal preventive maintenance policy through a mathematical model for a single wind turbine, also considering the stochastic weather influences.

Nevertheless, it is fully understood that only preventive maintenance is not satisfactory for offshore wind farm industry; because preventive maintenance cannot prevent all the failures, and there is always a risk that unexpected failures may occur. Instead, preventive maintenance can be defined as the actions, which lead to longer and uninterrupted (by failures) uptime.

2.3.3 Predictive maintenance

The indication of predictive maintenance is forecasting potential failures before occurring. Therefore, predictive maintenance appears to be the most attractive O&M policy for offshore wind industry (El-Thalji and Jantunen, 2012). It has fully proven potential towards minimised O&M costs. Operators can improve planning of the O&M policies, extend the lifetime of turbines and increase the profitability of the projects. However, extra costs associated with the equipment and the complexity/uncertainty of the analysis make predictive maintenance tremendously challenging.

Following two sub-sections provide detailed explanation of predictive maintenance, which includes broad range of concepts. In this respect, predictive maintenance is classified into *condition-based maintenance* and *reliability based maintenance*. They are different approaches to forecast/estimate the time that the failure occurs; but the ultimate aims are the same.

2.3.3.1 Condition-based maintenance

Condition-based maintenance is a decision making strategy, where the decision to perform O&M task is made by observing the condition of the overall wind turbine system and/or its sub-components. The condition of a system is quantified by specific parameters depending on the working characteristics of the applications that are continuously monitored. The main approach is gathering signals from components and diagnosing/predicting failures through analysing these signals, which provides information whether an O&M activity is required or not, and more importantly when this O&M activity has to be performed in order to prevent catastrophic failures. According to Daneshi-Far *et al.* (2010), condition based O&M is indispensable and compulsory element for the offshore O&M activities.

As a part of "Wind Turbine Operation and O&M based on Condition Monitoring" Project, Verbruggen (2003) reported available condition monitoring techniques and assessed appropriate techniques from wind turbine technology point of view. In addition, Wiggelinkhuizen *et al.* (2007) identified current condition monitoring systems in CONMOW Project. Following the identification period, a small wind farm consisting of five offshore wind turbines is equipped with the identified systems. Ciang *et al.* (2008) reviewed structural damage detection techniques for wind turbines and highlighted the benefits and drawbacks of each method. Crabtree (2011), Bin *et al.* (2009), Nilsson (2006), and McGowin (2006) examined the practical condition monitoring systems for wind turbines. Wiggelinkhuizen *et al.* (2008) described condition monitoring practices in offshore wind farms and assessed the usefulness, capabilities and economic consequences of the condition monitoring systems. In a recent study, Marquez *et al.* (2012) itemised condition monitoring techniques of wind turbines as vibration, acoustic emission, ultrasonic techniques, oil analysis, strain, electrical effects, shock pulse methods, process parameters, performance monitoring, radiographic inspections, thermography and others. Hameed *et al.* (2010) studied condition monitoring system issues for wind farms. This study pointed out that there are still design, installation and testing problems, for which significant effort has to be undertaken in order to implement these systems to entire wind turbine system.

The availability of a wind farm can be defined as the percentage of time it is able to produce power, and is a function of the reliability, maintainability and serviceability of the hardware and software used in the whole system (Hameed *et al.*, 2011). Although some extreme occasions may occur, offshore wind turbines generally show availability levels of 80 to 95% (Van Bussel and Zaaijer, 2001a, Van Bussel and Zaaijer, 2001b, Kaldellis and Kapsali, 2013). For that reason, the zone that condition-monitoring systems can be effective is very limited. Furthermore, there is a probability of false alarms (negative/positive), which may lead to either unnecessary O&M actions or production downtime (Nielsen and Sorensen, 2011). Popa *et al.* (2003) adapted and tested an existing fault detection method as part of wind turbine condition monitoring systems in order to avoid undesirable electrical faults. Wenxian *et al.* (2008) proposed an empirical mode decomposition technique that analyses the wind turbine non-stationary signals more accurately and efficiently compared to conventional Fourier transform-based techniques. Wengang *et al.* (2010) developed a methodology through using multiple operational parameters in order to overcome the high alarm rate caused by determining the alarm thresholds according to only one operational parameter in complex and non-stationary wind turbine operational conditions.

Another issue related to condition monitoring is the data acquisition and diagnosis. Continuous monitoring creates a significant challenge due to handling, storing and accessing large volumes of data (Gray and Watson, 2010). Swiszcz *et al.* (2008) discussed the data storage techniques that are used in condition monitoring systems and described a new data acquisition platform for offshore wind turbines. Wilkinson and Tavner (2004) demonstrated how data can be extracted through a condition monitoring system on a drive train. As a part of Condition Monitoring Project funded by Energy Technologies Institute, Miguelánez and Lane (2010) proposed a holistic condition monitoring system that contains extensive number of events and sensor values associated with the overall turbine system and their subsystems.

There is significant effort in order to improve the reliability and sustainability of new condition monitoring systems on wind turbines. Giebel *et al.* (2006) indicated that the standardisation is necessary for new production condition monitoring systems. Khan *et al.* (2005) studied a new condition-monitoring system for small wind turbines and tested the proposed equipment on a test bench. Tian *et al.* (2011) developed a condition based maintenance policy that addresses the issues associated with the number of turbines and components, economic dependencies, and O&M planning. Wenxian *et al.* (2008) proposed a new condition monitoring system, which eliminates issues related to variable wind speeds in machine condition monitoring. Papadopoulos and Cipcigan (2009) developed a model in order to detect the failures by specifying their exact position from sensors that are used in condition monitoring systems.

Besnard and Bertling (2010) proved that O&M cost of wind turbine blades can be decreased 60%, if condition-monitoring systems are utilised. McMillan and Ault (2007) proved that the theoretical net benefit of a condition-based maintenance policy is over £35,000 per annum, and the maximum benefit level would result in a lifetime benefit of around £1.5M per turbine. Besnard *et al.* (2010) notified that even if there is no economic benefit, the risk of high O&M costs can be lowered by the use of condition monitoring systems, which enables to diagnose system and identify potential failures in advance. Nilsson and Bertling (2007) indicated that 4.5% decrease in preventive O&M or 2.5%

decrease in both preventive and corrective O&M is sufficient in order to cover the costs of condition monitoring systems for a single offshore wind turbine.

Nielsen and Sorensen (2011) compared condition based and corrective O&M practices through considering the influence of damage development, detectable damage, inspection intervals, rate of interest, damage exponent, failure rate and cost; in the case of only one component of one offshore turbine is observed. It is demonstrated that the condition-based maintenance avoids most of the corrective maintenance activities; however, it results in larger number of repairs throughout the lifespan. In this study, a 20% cost reduction is achieved by implementing condition monitoring systems to the conventional corrective maintenance activities.

2.3.3.2 Reliability centred maintenance

Reliability centred maintenance is the approach to utilise reliability estimates for the systems and to formulate a cost-effective plan for O&M. The main approach is based on mathematical models to determine the minimum direct O&M costs and consequences of not performing O&M (production loss, revenue loss, etc.) through analysing failure rates. Although thorough studies have been carried out associated with reliability centred maintenance in various industries; there are still areas that have to be improved in order to make offshore wind energy competitive. Most of the studies associated with reliability, availability and failure rate assessment are categorised as electrical, mechanical, and structural failures.

Faulstich *et al.* (2011) studied the failure rates of wind turbine components and the duration of downtime related to these failures. Minor failures, which represent 75% of all failures, cause only 5% of overall downtime, on the other hand major failures that represent 25% of all failures account for 95% of all downtime duration. The failure distributions and the reasons behind these failures in offshore wind farms are listed in a study performed by Faulstich *et al.* (2009). To sum up, the failure rates increase when the complexity of turbine designs increases, which is a more expected situation for offshore wind farms compared to onshore models.

Regarding electrical evaluation, Franken *et al.* (2005), Sannino *et al.* (2006) investigated the availability of different electrical topologies. These studies demonstrated that the more advanced topologies provide higher reliability; however, the use of more circuit breakers together with more complicated control and protection arrangements increase the costs. The results of a research done by Spahic *et al.* (2009) showed that generators are the main causes for unavailability in the power systems. Although marine cable has very low failure rates, it is has a great influence on the reliability due to much longer Mean Time to Repair (MTTR) (Huang and Fu, 2010). Arabian-Hoseynabadi *et al.* (2010a) indicated that generators, power electronic converters and interface systems between the rotor windings and the converters have the highest influence on the availability of electrical composition of wind turbines. It was also demonstrated that fixed speed wind turbines are more reliable, even though they are less efficient than variable speed wind turbines. Arifujjaman *et al.* (2009) demonstrated that permanent magnet generators suffer from low reliability more than wound rotor induction generator based turbines. The analysis of Brown and Taylor (1999) showed that electrical configuration of wind farm substation is most sensitive to draw-out breakers and transformers.

With respect to mechanical composition of wind turbines, Haitao *et al.* (2009) analysed statistical failure rates and eventually recommended that gearbox downtime has to be considered in order to improve the system availability. Arabian-Hoseynabadi *et al.* (2010b) claimed that geared drive shows better availability than the direct drive for smaller wind turbines, but this is reversed for the larger direct-drive wind turbine concept. Smolders *et al.* (2010) examined the reliability performances of three different gearbox configurations. The gearbox, which contains the least components, showed the best reliability performance. In DOWEC Project, Van Bussel and Zaaijer (2001b) analysed the failure rates of six different wind turbine designs which vary in respect of power controls, number of blades, rotor speeds, types of inverters, towers, foundations, hubs and the positions of rotors. The results showed that the design with passive stall, two blades, constant/double speed, tubular tower, monopile foundation, upwind rotor position, fixed hub and without inverter has lowest failure rates. Ultimately, the comparison of O&M costs were grouped according to various categories. Irrespective of design, the cost of lifting operations by using an external crane accounted for more than 50% of the overall O&M cost (Van Bussel and Zaaijer, 2001b).

Ribrant and Bertling (2007) analysed the failure statistics of wind turbines located in Sweden, Finland and Germany. The assessment of reliability performances proves that drive train components rarely fail, however same components have the longest downtime due to the need for equipment replacement & spare part logistics and supply chain issues. The failure rates of wind turbines were analysed in DOWEC Project and reliability assessments were carried out for different wind turbines which are at different locations (DOWEC, 2003). From 'expected energy not supplied' point of view, Scheu *et al.* (2012) proved that generators have the largest impact on the availability of the wind farms.

Mabel *et al.* (2011) described the reliability concept in terms of 'period that supplied energy does not reach the level of given power level' and 'period that the energy demand exceeds the energy production' through analysing monthly production data of seven different wind farms. The study revealed that hub height is positively correlated to improved wind power plant reliability. Tavner *et al.* (2007) analysed failure data of different offshore wind farms, and predicted the failures through two different models. Subsequently, the analysis results and the prediction methods were discussed in order to clarify the effects of turbine design, turbine configuration, time, weather, and O&M on reliability distributions. This research showed that the impact of mechanical subassembly maintenance is time consuming and costly due to extended MTTR, despite the fact that electrical control or system subassemblies have highest failure rates.

Negra *et al.* (2006) evaluated the performances and the strengths of the following reliability assessment methods: sequential Monte-Carlo simulation and analytical method with frequency and duration analysis. Both methods provide similar results with maximum 1.5% difference. The computational time of analytical method is longer; on the other hand, when the time resources are generated, they can be utilised for further calculations. In Monte-Carlo method, all the simulations must be performed each time. Additionally, Negra *et al.* (2007), Holmstrøm and Negra (2007) reviewed the available models for wind farm reliability assessment. They mentioned that wind speed simulation, wake effects, wind turbine technology, offshore environment, different wind speeds in the installation site, power collection grid in the wind farm, correlation of output power for different wind turbines, grid connection configuration, hub height variations are the relevant factors, which influence the accuracy of assessments. Wilkinson *et al.* (2006) performed a FMEA study to highlight the strong points and potential risks of alternative turbine designs and concepts. Guo *et al.* (2009) presented a three-parameter Weibull model in order to make accurate predictions for the reliability trend over a specific period.

2.3.4 Assessment of existing O&M practices

Table 2 shows the advantages and disadvantages of each O&M approach. Predictive maintenance methodologies are suggested to be the best available methods in order to prevent failures before occurring. On the other hand, these methodologies require advanced computer systems, enhanced analysis and diagnosis capability, and specialists in order to use and assess the circumstances/consequences, which increase the cost of the O&M activities. In addition, despite proven theories, none of the methodologies alone is satisfactory in real life in order to prevent all failures before occurring. Therefore, corrective maintenance always has to be a part of total O&M planning. In order to operate the wind turbines in robust physical condition, which also decreases the probability of failures, preventive maintenance actions have to be a part of O&M planning. Therefore, the most cost-effective methodology can be a hybrid approach that minimises corrective maintenance as much as possible, while optimising preventive maintenance and supporting them with predictive maintenance practices. At this point, it is important to highlight that there is a trade-off between the accuracy of the models and the costs associated with them. Systems that are more complicated might be more reliable with regard to failure forecasting, however the costs associated with them might be very high. Therefore, many applications focus on O&M optimisation of specific components or an individual wind turbine system, rather than the entire wind farm (Ding, 2010).

Table 2: Advantages and disadvantages of different O&M practices

	Advantages	Disadvantages
Corrective maintenance	- Low direct cost - Limited personnel requirement - Maximum use of components	- Increased total costs due to unplanned downtime of equipment - Increased labour cost, especially if overtime is needed - Cost involved with repair or replacement of equipment - Possible major component damage from equipment failure - No O&M scheduling is possible - Spare parts logistics is complicated - Long delivery period for spare parts

	Advantages	Disadvantages
Preventive maintenance	- Cost effective in many capital-intensive processes - Flexibility allows for the adjustment of O&M periodicity - Overtime can be reduced or eliminated - Increased component life cycle - Energy savings - Reduced equipment or process failure - Helps ensure quality output - Low downtime - Smaller stock of parts is required - Scheduled O&M - Easy spare part logistics	- Catastrophic failures still likely to occur - Labour intensive - Includes performance of unnecessary O&M - Potential for incidental damage to components in conducting unnecessary O&M - Higher O&M costs - Requires more frequent access to equipment - Components cannot be used for maximum lifetime - The risk of neglect, ignorance, abuse, or incorrect procedures
Predictive maintenance	- Increased component operational life/availability - Decrease in equipment or process downtime - Decrease in costs for parts and labour - Lower insurance rates - Better product quality - Improved worker and environmental safety - Asset Protection - Energy savings - Full lifetime use of components - Low expected downtime - Scheduled O&M - Easy spare part logistics	- Increased investment in staff training - Savings potential not readily seen by management - Reliable data about the remaining lifetime of the components is required - High investment for condition monitoring hardware and software is required. - Identification of appropriate condition threshold values is difficult

2.3.5 Existing wind farm O&M tools and models

To support operators in optimising O&M activity, different models have been developed to analyse and plan offshore wind O&M activities. Pahlke (2007) provided an overview of existing decision support systems and individual software tools in POWER Project. Through the evaluation of questionnaires, the demand and requirements of decision support systems are also listed in the research. According to Pahlke (2007), 64% of the participants would like to use decision support systems in their work and 73.9% of these participants would like to implement decision support systems especially in the area of planning, even though only few of them have models to use. The need for Software Decision Support Systems is found in nearly all main areas of offshore wind energy with focus on project development, approval procedure, ecological evaluation, financing, maintenance and operation, cable route and logistics.

At the first place, TU Delft developed CONTOFAX tool which utilises Monte-Carlo simulations to analyse state of every component over a period of time (Bussel and Schöntag, 1997). Considering that it was an early attempt to model offshore wind farm operations, it was not possible to define time dependent failure rates for turbine components (Koutoulakos, 2007); in addition, the travel distance was constant for all the turbines in the defined offshore wind farm.

Garcia *et al.* (2006) developed the tool Intelligent System for Predictive Maintenance (SIMAP), which optimises the O&M schedule according to operational condition of wind turbine considering the technical and economic conditions of the operators. This application requires continuous data collection and diagnosis, which can be inefficient considering the fact that operators may not have the expertise to interpret the signals.

In the Dutch Offshore Wind Energy Convertor (DOWEC) project, a Monte-Carlo approach, in which realistic maintenance actions are determined under random simulation of wind and wave conditions, random wind turbine failures, predefined maintenance crew deployment and given availability of maintenance equipment, is implemented in order to calculate the total O&M costs, the achieved availability and the produced energy of the wind farm (Bussel and Bierbooms, 2003a). Inflatable boats, special offshore transportation systems and helicopters for offshore wind farm O&M activities are investigated and flexible gangway solutions on a standard pilot vessel are entitled as a good opportunity to obtain good availability in order to facilitate the O&M crew access (Bussel and Bierbooms, 2003b).

Another O&M Cost Estimator developed by National Renewable Energy Laboratory and Global Energy Concepts considers the typical costs associated with ongoing operations, including scheduled maintenance, unscheduled repairs, site management, and support personnel, of a facility that comprises any number of conventional wind turbines (Poore and Walford, 2008). This estimator includes a database that represents the values for turbine, site service and repair parts. The required user inputs are characteristics related to the wind farm (number of turbines, assumed site capacity factor and expected sell price per kilowatt-hour) and turbine characteristics (rated capacity, hub height, pitch system, and type of power conversion). However, this application was developed for on-shore wind farms; therefore crucial aspects such as accessibility and vessel unavailability are not considered.

As an output of the Structural and Economic Optimisation of Bottom-Mounted Offshore Wind Energy Converters (Opti-OWECS) project, Kühn et al. (1999) discussed the design solutions for offshore wind farms, as well as taking the feasibility, economic performance, costs associated with operation, O&M and analysis tools. The need for understanding the offshore environment is highlighted in order to facilitate more reliable energy yield predictions, optimum designs and optimum strategies for operation and O&M.

The MWCOST tool (extension of SLOOP software) is another tool developed by BMT Group in order to perform probability distributions of the wind farm's performance and identify alternative scenarios for financial assessment, and directed engineering and operations design (Stratford, 2007). In this study, it is recommended that the turbine failure modes can be grouped into five different segments; complete replacement of assets, major interventions requiring external crane, major interventions not requiring external crane (e.g. internal crane fitted to turbine), minor interventions requiring just crew, remote reset or auto reset. The MWCOST tool uses a time-series of environmental parameters, which include the persistence of the environmental parameters (i.e. the length of time for which the wind speed is low etc.) and also the correlation between the parameters.

Maintainability, Availability, Reliability, Operability, and Simulation (MAROS) is an advanced RAM tool for oil and gas assets with extensive features for modelling networks, maintenance, operations and demand scenarios which includes powerful Boolean logic option. MAROS starts by looking at process flow diagrams and design based information, reliability block diagrams, reliability data, flow profiles, and maintenance strategies (DNV, 2013). These inputs are analysed by Monte-Carlo method in order to obtain results relating equipment criticality, production efficiency, OPEX of the asset throughout the lifecycle.

As a part of 'Recommendations for Offshore wind turbines' (RECOFF) project, ECN developed a tool in order to model the following corrective maintenance aspects of offshore wind farms; downtime, revenue losses and costs (Curvers and Rademakers, 2004b). WeWiCDF pre-processing package in this tool analyses the time series of the wind speed and wave height for a certain weather window. In addition, Twait pre-processing package calculates the waiting time as function of the mission time by means of Monte-Carlo simulations. In this tool the probability of having sufficient weather window is represented by a Weibull distribution.

In the ECUME tool, which is based in ECN O&M cost model, total cost of the maintenance operations were evaluated. However, mean cost values are not sufficient to determine the maintenance strategy, because decisions are exposed to the uncertainty of component failures and inaccessibility of sites (Douard et al., 2012). Therefore, the following two models are implemented into the existing ECUME decision model; a failure model simulating failure instances according to a mix of Weibull distributions and a meteorological and marine model simulating meteorological scenarios according to the past. This adaptation allows consideration of random behaviour of the farm and the weather together by providing risk indicators.

Energy Research Centre of the Netherlands developed a powerful tool, which can be a subsection of an O&M management system in order to estimate the operation and O&M costs for the future 1-2-5 year life cycle of the offshore wind farm projects (Obdam *et al.*, 2007, Rademakers *et al.*, 2008, Rademakers *et al.*, 2009). The ECN O&M Tool is generally considered to be the most comprehensive tool for analysing O&M costs and downtime (Curvers and Rademakers, 2004a, Curvers and Rademakers, 2004c, Ramakers *et al.*, 2004) and has received a validation statement from Germanischer Lloyd (Rademakers et al., 2011).

In a report prepared by Sandia National Laboratories, Walford (2006) identified the costs of O&M, the aspects that compose the overall O&M costs, the possible approaches to reduce the O&M costs and additional actions, which have to be considered in the future. Quantification of operation and O&M costs over time, development of component reliability models, identification of high-risk components, evaluation of design standards and maintainability improvements are suggested tasks to minimise wind turbine operation and O&M costs.

In addition to what has been introduced so far, Feuchtwang and Infield (2012) proposed an event tree probabilistic delay model for four most likely situations concentrating the relation between sea state and required repair time. Tallhaug *et al.* (2005), Laakso *et al.* (2010) and Tammelin (2002) provided recommendations for the structural, operational risks for wind turbines working in cold and icy environment. Sørensen (2009) proposed a risk-based life cycle framework for the planning of operation and O&M activities considering the deterioration and the future costs associated with inspection, monitoring, O&M, repair and failures of wind turbines through pre-posterior Bayesian decision theory. GL-Garrad Hassan developed O2M tool, which is based on work conducted by Bossanyi and Strowbridge (1992). The O2M tool takes the wave height values into account and performs time domain Monte-Carlo simulations (Philips et al., 2006). Besnard *et al.* (2009) developed a model in order to optimise the preventive maintenance costs through the examination of power production, preventive maintenance and corrective maintenance activities which can potentially create large cost savings.

Furthermore, the STRATH-OW, which has been under development since June 2013, is identified as the most comprehensive tool developed so far. The STRATH-OW tool has been initiated by a team, which comprises of researchers from Naval Architecture, Ocean and Marine Engineering, Electronic and Electrical Engineering, and Management Science Departments within the University of Strathclyde. In addition, Scottish and Southern Energy (SSE), Scottish Power Renewables (SPR)/Iberdrola and Technip have assisted the tool development with their operational expertise in the offshore wind O&M industry. Although the tool has still been under development, the initial developments and results are presented in the following publications by Dalgic *et al.* (2015b), Dalgic *et al.* (2015a) Dalgic *et al.* (2014a), Dinwoodie *et al.* (2014), Dinwoodie *et al.* (2013).

Although there has been a significant effort to model and simulate offshore wind farm O&M activities, it is believed that the properties of the vessels and the integration of these vessel to the O&M activities are generally over simplified. In this respect, review of the literature is required in order to identify the different O&M vessels available in the market and implement their properties to the proposed model. In the following section, a review of the vessels available in the offshore wind O&M market is performed.

2.4 Offshore wind O&M fleet selection

There are several attributes which have to be considered in the O&M fleet selection process. Figure 14 demonstrates the majority of these attributes in a single framework. Vessel specification, financial attributes, environmental conditions, and failure characteristics are the four major segments in the vessel selection process. There are also several sub-sections related to each segment. It has to be highlighted that the number of segments and sub-sections can vary depending on the scope of the analysis.

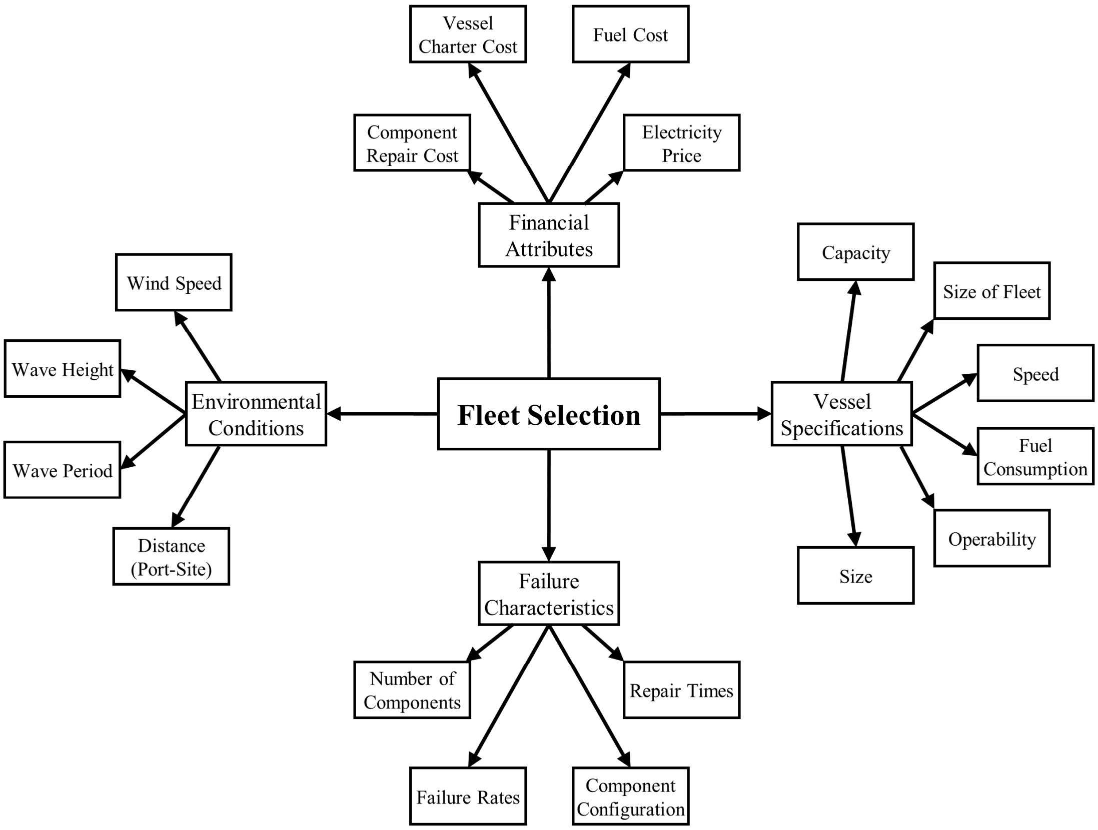

Figure 14: Attributes in the fleet selection process

2.4.1 Vessel specifications

Vessels are the floating structures, which are utilised in environmental and site surveys, transportation and assembly of wind turbine components as well as planned and unplanned maintenance operations. Offshore wind turbine operators have to take the alternatives into consideration due to vast number of available vessels, properties and the variety of benefits and drawbacks associated with each vessel type. In the following section, O&M vessels available in the offshore wind market are presented.

2.4.1.1 Available vessels in the offshore wind market

During the operational span of an offshore wind farm, a number of planned and unplanned maintenance tasks have to be performed in order to keep the turbines operational and to sustain the power production. In this respect, there are two main O&M vessel categories in the offshore wind energy market:

- Vessels for minor maintenance
- Vessels for major maintenance

- Vessels for minor maintenance operations

Regarding vessels for minor maintenance, current transportation methods to offshore wind turbines include mostly the use of small workboats, which involves long shuttling journey times resulting in considerable wasted productive time. Monohull boats, small catamaran vessels, and small water-plane area twin hull (SWATH) vessels are generally utilised in minor maintenance operations, which allow operators to keep the cost of minor maintenance operations at optimum level (Figure 15). The most distinctive characteristics of these vessels are high speed, small deck spaces, small crane capacities and safe access to wind turbine structures that allow operators to take quick actions in the case of unexpected failures and to perform seasonal O&M campaigns.

Offshore wind farm access is severely impacted by very poor weather tolerance, particularly in further offshore locations (Walker et al., 2013). Due to relatively smaller size, these vessels are more susceptible to harsh environment, which has to be improved in the next generation vessels. Furthermore, 1.5 metre operational wave height restriction limits the number of working days by 200, which can be increased to 310, if safe working wave height limit is improved to 3 metres (Cameron, 2011). As Heinecke (2010) investigated, the expectations of operators and technicians can differentiate; such as, while safety, transport time, fuel consumption and availability of vessels are important for operators, comfort, separation of cargo and basic catering services are essential for the technicians. These vessels use the engine trust to maintain position and allow technicians to step across the turbines. This procedure have to be improved through stabilised access gangways and other innovative solutions, considering that the floating offshore wind turbine access represents a more important issue due to the fact that both vessels and wind turbines move continuously under the effect of wave and wind (Vries, 2009).

Figure 15: Vessel for minor maintenance operations (Monohull – Catamaran - SWATH) (MPI Offshore, 2012, BARD Group, 2013, Incat Crowther, 2013)

In some circumstances, operators consider a helicopter in the O&M fleet in order to provide access, when the CTVs are not able to sail due to rough climate conditions. Both transportation systems (CTVs and helicopter) involve significant amount of costly and inefficient travel for technicians; in addition relatively small vessels pose a significant risk of capsizing in rough weather conditions (Al-Salem et al., 2006).

In addition to conventional CTVs, Offshore Access Vessels (OAVs) are occasionally considered by the offshore wind operators in their O&M fleets. These larger vessels (~50 m) have better operational capability than conventional CTVs and are generally equipped with dynamic positioning systems. Additionally, motion-compensating gangways are typically installed on OAVs in order to transfer technicians on the wind turbine in rough weather, in which CTVs cannot operate (Dai et al., 2013, O'Connor et al., 2013). Cranes on these vessels provide ability to transfer medium weight components from vessels' deck directly to offshore wind turbine platforms. OAVs are designed to stay in the offshore wind farms longer periods and therefore travels between sites and O&M ports can be minimised. These advantages make OAVs an adequate candidate for the offshore wind O&M activities. However, the charter cost of these vessels are higher than CTVs, which is a major issue considering the fact that the operators intend to minimise the O&M costs. The generic criteria related to human performance are well established for seamen but not so well established for O&M technicians (Wu, 2014). In addition, quality and duration of sleep are impaired by disturbance associated with ongoing tasks and environmental factors (e.g. noise, shared cabins, poor air quality) in offshore environment; and therefore has adverse effects on day-to-day performance and alertness of the O&M technicians (Belenky et al., 2003, Anderson and Horne, 2006, Parkes, 2010, Townsend et al., 2012). Moreover, the use of OAVs is not well defined due to immaturity of the industry. Therefore, OAVs are not considered as a permanent solution like CTVs; instead, these vessels are chartered for shorter periods.

According to a report prepared by WindPower Offshore (2013), the proportion of the CTVs to the number of vessels in the entire offshore wind market is 40.6%, while cabling vessels, jack-up vessels, heavy lift vessels and other vessel account for 21.3%, 16%, 12%, and 10%, respectively. Despite the dominance of the CTVs, there is no regulation specifically for offshore wind farm service vessels (WorldWind Technology, 2013). Technicians performing offshore maintenance are classed as passengers, and therefore if there are more than 12 technicians on-board, this specific vessel is classified as passenger vessel, which introduces extensive safety legislation and decrease operational flexibility. Furthermore, weather conditions restrict CTV access to turbines; larger vessel may have better operational capabilities but charter rates escalate quickly. In this respect, it is essential to use the optimal vessels for the jobs involved, but also charter them at the right time at the minimal price.

- Vessels for major maintenance operations

In the case of major component failures, vessels for minor maintenance operations are not adequate to perform the repair/exchange of damaged component. Therefore, one of the jack-up, leg-stabilised or heavy lift vessels have to be utilised, considering the properties of damaged component (weight, size, etc.), lifting height, and the capability of the vessel (lifting capacity, operational water depth, etc.).

Jack-ups

Jack-ups are self-elevating units, which consist of a buoyant hull with a number of legs (generally 3 to 6), are capable of raising their hulls over the sea-surface, station their legs on the sea floor and providing very stable environment for crane operations under challenging climate conditions.

Jack-up barges

Jack-up barges have been utilised in every task of maintenance phase, and have been dominating offshore industry since first offshore wind farm has been installed. Due to the lack of self-propulsion systems, the manoeuvrability of jack-up barges is dependent on the supporting vessels and tugboats (Figure 16). Although current available jack-ups are designed for offshore operations, they are not ideally equipped and cannot be sufficient to perform offshore wind turbine operations in deeper waters due to their limited operable depths and crane capabilities.

Figure 16: Jack-up barge (A2SEA, 2012b)

Jack-up vessels

Jack-up vessels incorporate self-propulsion systems with dynamic positioning, sufficient deck space and better lifting capabilities in order to perform every phase of maintenance operations (Figure 17). Self-propulsion and dynamic positioning systems make jack-up vessels independent from availability and limitations of towing vessels. These vessels are capable of transporting, assembling, and installing wind turbine components, transition pieces, foundations and assembled sub-systems; therefore, by considering a jack-up vessel in the O&M fleet, the number of days in operation can be maximised, also the number of vessels required for the O&M can be minimised. Although jack-up vessels are the most appropriate candidate for the offshore wind farm operations, they are still low in numbers due to very high construction costs, daily operation costs and future economic uncertainties in the offshore wind market.

Figure 17: Jack-up vessel (HGO InfraSea Solutions, 2012)

Leg-stabilised vessels

The operations of leg-stabilised (semi jack-up vessels) are very similar to the jack-up vessels/barges (Figure 18). Instead of lifting the hull over the sea surface, leg-stabilised vessels, which are ideal for shallow sites, use their legs to stabilise their hulls. However, they have limited sea state for crane operations due the fact that their hulls remain submerged and are subject to wave-induced motion (Tetra Tech EC INC. et al., 2010).

Figure 18: Leg-stabilised vessel (A2SEA, 2012a)

Heavy lifters

Heavy lifters are capable of lifting extensive loads, which can be experienced in offshore wind industry. These vessels have the highest crane capability (SSCV Thialf with 14,200 tonnes lifting capability) in offshore industry due to the fact that these vessels are specially designed to install pre-assembled modules for offshore oil and gas industry; however the daily charter rates are directly proportional to the crane capabilities.

Heavy-lift cargo vessels

Heavy lift cargo vessels, which are conventional cargo ships with sufficient crane capacity for offshore wind farm installations and have sleeker hull forms compared to the majority of crane barges/vessels, have been used in oil and gas industry for the offshore platform installations (Figure 19). These vessels are appropriate for piling operations, foundation and transition piece installation phases; on the other hand, wind turbine component installations can exceed the maximum hook heights and also may lead to loss of stability (EWEA, 2011).

Figure 19: Heavy-lift cargo vessel (Jumbo Shipping, 2012)

Heavy-lift crane barges/vessels

First type of heavy lift crane barges/vessels utilise large sheer-leg or pedestal mounted cranes which provide an extensive range of heavy lifting applications in offshore oil and gas industry as well as offshore wind industry (Figure 20). Due to limited space on main deck and slower navigation speed relative to other vessel types, feeder vessels are generally required to transport wind turbine components in order to reduce the installation/maintenance period. On the other hand, dynamic positioning systems, and the combination of lifting capacities up to 5,000 tonnes & hook heights over 170 metres allow these vessels to operate in different environments and tasks (Verhoeven, 2012).

Figure 20: Sheer-leg heavy-lift crane barge (SMIT Heavy Lift Europe, 2012)

Second type of heavy lift crane barges/vessels utilise mobile cranes (generally crawler crane) which is a classic method to construct river and coastal marine projects. These vessels can fulfil the role of feeder vessels in offshore wind farm projects (Figure 21). Furthermore, these vessels can take active role in maintenance phase, especially in minor roles; however the stability of the configuration has to be considered in major maintenance tasks.

Figure 21: Heavy-lift crane barge with mobile crane (Turn Key Maritime Solutions, 2012)

Semi-submersible crane vessels

Semi-submersible crane vessels are specifically designed for oil and gas industry in order to perform oil and gas module installations in harsh offshore conditions. These vessels show great stability characteristics through ballasting and submerging the pontoons into the seawater (Figure 22). Despite heavy lifting capacity, huge deck space, these vessels are not popular in offshore wind farm operations due to very high operational costs and slow mobilisation and transport opportunities (Bard and Thalemann, 2011).

Figure 22: Semi-submersible crane vessel (Saipem S.p.A., 2012)

2.4.1.2 *Current vessel market condition and future prospects*

There are currently 48 jack-up barges/vessels and 122 crew transfer vessels available in the market (WindPower Offshore, 2013). The Crown Estate (2014) identified only 35 jack-up barges/vessels are able to meet the offshore wind sector requirements and standards. It should be highlighted that not every vessel is suitable for every job and the vessels available are not necessarily dedicated to offshore wind sector alone. Furthermore, these vessels are shared with the offshore oil and gas industry. Therefore, there is a risk of vessel unavailability in case of high demand. According to WindPower Offshore (2013) report, a 40% increase is expected in the vessel demand by the offshore wind sector. Bard and Thalemann (2011) reported that 550 crew transfer vessels and 150 jack-up vessels will be required by 2020. In addition, 35 mothership will be required due to far offshore installation. As the turbines become bigger, foundations become heavier and projects move to deeper waters, vessels currently available will not be sufficient to perform operations.

2.4.1.3 *Assessment and comparison of available vessels*

The properties and the variety of benefits & drawbacks of the vessels have to be taken into account in the fleet selection process, which allow operators eliminating either insufficient, oversize or unnecessary vessels. Selection of these vessels (insufficient, oversize or unnecessary) increases the cost of operations significantly. Benefits and drawbacks of the vessels for minor maintenance operations are listed in Table 3. Monohull configurations have higher wave resistance and require a larger engine to reach high speed (Moraes *et al.*, 2007, Dubrovsky, 2010). Catamaran configurations are often preferred choice by the offshore wind farm operators (Tavner, 2012); this is because, roll motion is minimised, which provides a more stable working environment/platform compared to monohull configurations (Marsh, 2012). Due to small splash zone, SWATH vessels are more stable than other type of minor maintenance vessels; however, their cargo capacity is very limited and more importantly requires significant CAPEX/OPEX (Thomsen, 2012). It is a generic principle that the vessel with the lowest CAPEX has the lowest daily charter rate compared to the other vessels in the same market (Hovland, 2008). Therefore, catamarans have been dominating the market since the establishment of the offshore wind industry.

Table 3: Characteristics of vessels for minor O&M activities

Vessel type	Benefits	Drawbacks
Monohull	- Very high speed (~ 30 knots) - Reasonably lower charter rates - High availability in the offshore market	- Limited passenger (6 to 8) - Limited cargo capacity - Uncomfortable for passengers, no other facilities available - Limited safe access to turbines (H_s<1m)
Catamaran	- High speed (~ 20 knots) - Operational H_s=~1.8 m - Safe access to turbines (H_s<1.5m) - High availability in the offshore wind market	- Limited passenger (12 and more) and cargo capacity - Limited cargo capacity - Relatively higher charter rates
SWATH	- Capacity of 12 to 60 passengers - High speed (~ 20 knots) - Operational H_s=~2.0 m - Safe access to turbines (H_s<1.8m) - Comfortable for passengers	- Limited cargo capacity - Low availability in the offshore wind market - Relatively higher charter rates

Table 4 demonstrates the comparison of characteristics of vessels associated with major maintenance operations. Especially, it is important to highlight the fact that the number of leg stabilised vessels is considerably low in the offshore wind market (EWEA, 2011). Furthermore, Heavy lifters are capable of lifting extensive loads, which can be experienced in offshore wind industry; on the other hand the charter rates of heavy lifting vessels are excessively high (DNV, 2011, Dalgic *et al.*, 2014b). Therefore, jack-up vessels/barges dominate the offshore wind energy market. However, the dependency on the offshore oil and gas industry result in issues associated with lower vessel availability and higher daily charter rates in demanding months (e.g. April to October). Therefore, advanced charter planning is crucial, especially as the UK Round 3 projects and similar size forthcoming projects around the world are emerging.

Table 4: Characteristics of vessels for major O&M activities

Vessel type	Benefits	Drawbacks
Jack-ups	- Specialisation for offshore wind farm projects - Stable base for lifting operations - Cost effective in medium and high wave areas - Accommodation for both ship and maintenance crew	- Limited operational speed (~ 12 knots) - Capability to operate up to 65 m water depths - Time consuming operations due to jacking up and jacking down
Leg-stabilised vessels	- Ideal in shallow waters -Quick transportation and installation capabilities - Relatively lower daily charter rate	- Limited number of vessels in the market - Limited sea state capability (~ 0.5 m) - Risk of inadequacy due to increasing water depths of the future projects
Heavy-lifters	- Very flexible for unusual cargoes - Heavy lift capacity - Larger deck area/space - Relatively better stability characteristics	- Low availability due to offshore oil & gas industry - Slower mobilisation - Port entrance limitations due to size - Operations can be performed only in deep water

2.4.2 Financial aspects

Financial aspects comprise of CAPEX, OPEX and revenue loss that influence the O&M fleet selection. O&M activities represent a significant share of the ongoing expenses during the lifecycle of the offshore wind projects (Kaldellis and Kapsali, 2013). The O&M costs comprise of labour costs (technician costs), material costs (component cost), transportation costs (vessels and associated cost), fixed costs (port, insurance, bidding, etc.) and potential revenue loss. In this respect, it is important to identify the critical aspects that can significantly reduce overall costs. It has been identified that the costs associated with transportation systems account for 73% of the total O&M costs (Junginger et al., 2004, Fingersh et al., 2006, Krohn et al., 2009, Lazakis et al., 2013). In addition, Van Bussel and Zaaijer (2001b) demonstrated that the cost of lifting operations using a vessel accounts for more than 50% of the overall O&M costs. Therefore, O&M activities have to be planned carefully, considering the fact that economic benefit from producing more energy by increasing the availability does not always leads to higher profits, since the increase in the total O&M costs may not be compensated (Santos et al., 2013).

As in other industries, all the economic decisions are based on trade-offs between risk and cost. The most cost-efficient decisions are generally associated with the biggest risks. Conversely, the safest decisions may require the highest investments/costs. Neither of these options are acceptable for the offshore wind farm operators due to financial impact of the projects and cost of maintenance operations. For instance, if an operator makes a risky decision and selects a vessel with the lowest operational capability, which can reduce the vessel associated costs, then the revenue loss can reach extreme levels due to very low accessibility during the lifecycle of the project. On the other hand, if an operator makes a safe decision and selects a vessel with highest characteristics, which can provide sufficient support for the O&M tasks, but this situation may lead to a significant increase in the charter and fuel costs.

The decision process related to fleet size is also important. Small O&M fleets may lead to cost reductions in the vessel associated costs such as charter cost and crew cost; on the other hand, turbine failures may remain unrepaired due to lack of resources, which increases the downtime and the unavailability. The alternative option would create redundancy which is not acceptable, especially when the main target is to decrease the cost of maintenance operations. Therefore, it is not enough to decide the type, size, etc. of the vessel; the decision process has to be supported by the choice of the number of vessels, which are utilised in the O&M fleet.

2.4.2.1 Vessel chartering and contractual arrangements

The majority of the offshore wind farm operators do not prefer to own an O&M vessel due to initial capital investment requirement. Therefore, these vessels are chartered for a limited period. Unplanned maintenance activities, catastrophic failures, and circumstances that require instant access to wind farms cause operators to hire vessels from the spot market for relatively short periods. In this context, short-term chartering is valuable for the wind farms that have sequential maintenance activities in a specified period. Long-term chartering requires advanced scheduling for the maintenance operations. In this case, the daily charter rate decreases; however the financial risks due to low utilisation become more significant. An alternative to reduce the risks is leasing the vessel to third parties, which can provide extra income for the operators.

Voyage charter, time charter and bareboat charter are the commonly used three types of contractual arrangements in the maritime industry (Pirrong, 1993). The costs and individual responsibilities are distributed in a slightly different way (Figure 23). Under a voyage charter, the vessel owner is awarded a contract to carry a specific cargo with a specific ship, which covers capital charges, daily running, and voyage costs. The time charter is an agreement between owner and charterer to hire the vessel, complete with crew, for a fee per day, month or year. In this case, the vessel owner pays the capital and operating expenses, whilst the charterer pays the voyage costs. As a final point, the bareboat charterer hires out the vessel without crew or any operational responsibilities, so the charterer is responsible for daily running costs, voyage costs, O&M costs and expenses related to cargo handling and claiming.

For short-term activities, time charter or voyage charter appear practical due to the difficulty to arrange crew, provide provisions and complete administrative jobs for short-term; on the other hand, bareboat chartering which provides more control on the costs elements, is a more feasible alternative for long-term operations.

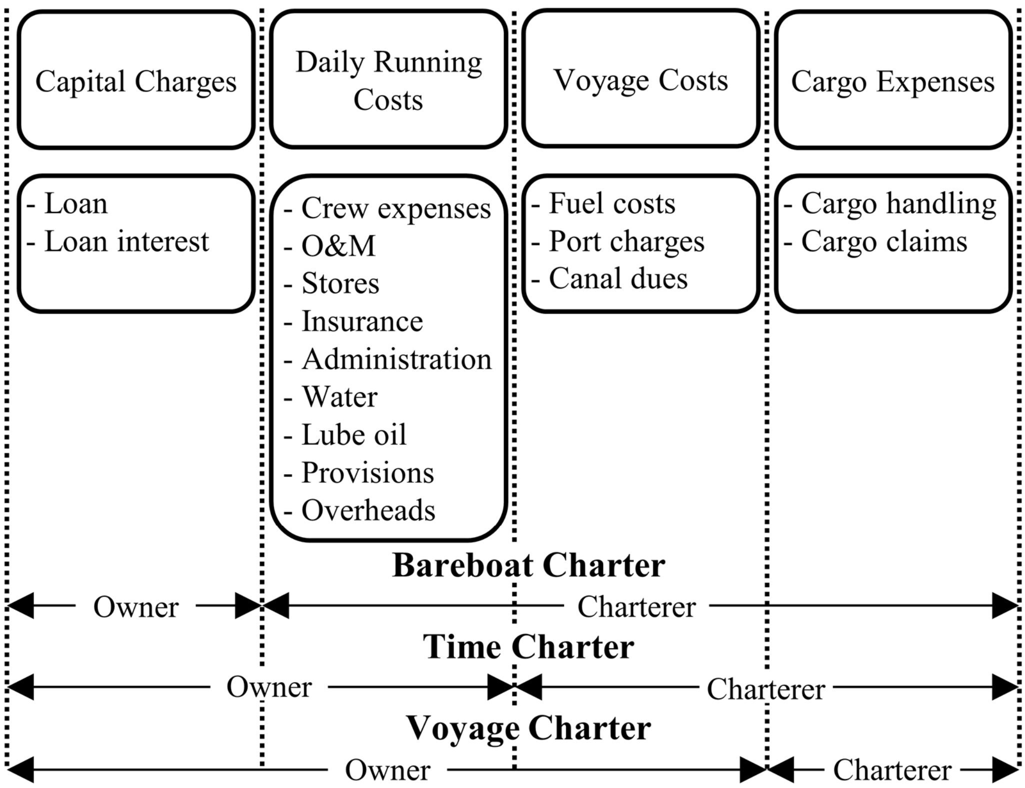

Figure 23: Vessel contractual arrangements

2.4.3 Environmental conditions

Environmental conditions are another important measure, which influence the O&M activities. Wind speed, wave height and wave period are major environmental constraints, which not only affect the journey specific issues, but also the power production of the offshore wind farms. In a generic content, areas with stronger wind characteristics are more valuable for power production. However, stronger wind is a constraint for O&M, similar to higher wave heights with shorter wave periods. Furthermore, stronger wind speed values have a negative effect on the failure characteristics of the wind turbine components (Arwade *et al.*, 2011).

There has been a significant effort to model the climate parameters, which can even be described as a more sophisticated research area than offshore wind O&M. In addition, the main target of this thesis is not to develop an innovative climate modelling approach, which is outside the scope of this study. Therefore, in the following sub-section, core information about climate modelling is provided; however, climate modelling can be elaborated further.

2.4.3.1 Climate modelling

Characteristics of the specified offshore wind farm have significant importance on the determination of the O&M fleet. The harsher the conditions become; the more serious accessibility and performance issues occur, due to capabilities/limitations of the vessels involved in the operations and effective safety working rules. Especially for new generation wind farms, O&M at offshore environment introduce significant risks to offshore wind farm developers. One important step in the mitigation of risks is capturing real data and analysing accurately for all stages of the project's life cycle. Generally, data is captured through offshore monitoring platforms/masts, which gather and transfer information related to wind speed and direction, barometric pressure, temperature, humidity, precipitation, visibility, wave height and direction, currents, bird movements, water temperature, and salinity in specified time intervals/periods. In order to model entire life cycle of the wind farm project exactly, 20-25 year multi-data monitoring is required, however this is a time consuming procedure and even if a 25-year model is created through real 25-year real data, there is no guarantee that the following years follow the exactly same path due to climate's stochastic nature. Therefore, a limited period of time, which can represent the overall cycle, has to be selected; so, associated data can be simulated through modelling techniques.

The sequence of climate observations generates a time series. It is essential to understand the dynamics of the system and model it effectively in order to make sensible forecasts about its future behaviour. Time series models can be either deterministic or stochastic. If the mathematical model of a physical process can predict the output of the process, it is called deterministic model. In the cases that the model can describe the behaviour of this process instead of predicting, it is called stochastic modelling, in which a prediction interval and probability of the future observations are provided. In this context, these methods are generally divided into following three main groups depending on the methodologies they propose and the time-scales they are focused on: persistence, physical, and statistical approaches.

- Time-scale classification

Although the differentiation between time-scales is not clear, they can be separated into four main categories (Soman *et al.*, 2010):

- Very-short term: Few seconds to 30 minutes ahead
- Short-term: 30 minutes to 6 hours ahead
- Medium-term: 6 hours to 1 day ahead
- Long-term: 1 day to 1 week or more ahead

- Persistence approach

Persistence approach is the simplest way to predict future values among all forecasting techniques (Yuan-Kang and Jing-Shan, 2007). The approach assumes that the value at time $t + \Delta t$ is same at time t. This method is very accurate in a very short-term; on the other hand, its effectiveness decreases significantly when the prediction interval increases.

- Physical approach

Physical approach consists of several sub-models, which together deliver the translation from the Numerical Weather Prediction (NWP) forecast at a certain grid point and model level. Every sub-model contains a mathematical description of physical processes relevant to the translation. Physical models use physical considerations such as terrain, obstacle, pressure, and temperature to estimate the future values (Yuan-Kang and Jing-Shan, 2007). They can be an initial step for climate forecasting, which is supplied as an auxiliary input of other statistical models. Physical approaches are designed to analyse atmospheric dynamics and boundary-layer meteorology towards large area weather forecasting (over many counties) for long time scales. Numerical weather prediction methods contain complex mathematical models that require complex calculations and equations, subsequently supercomputers and sufficient tools.

- Statistical approach

Statistical approach consists of emulating the relation between meteorological predictions, historical measurements, and generation outputs through statistical models, whose parameters have to be estimated from original data, without considering any physical phenomena. Statistical approaches are based on the training of historical datasets. They do not require a predefined mathematical model; instead, the predictions are provided through the identification of historical patterns and the differences between the predicted and the actual values in the immediate past (Potter and Negnevitsky, 2006, Lange and Focken, 2008). It is easy to model, computationally inexpensive, and provides sensible predictions. If patterns are met with historical ones, errors can be minimised.

Time-series based and neural network based methods are two subcategories of this approach. Moving Average (MA), Auto-Regressive (AR), Auto-Regressive Moving Average (ARMA) and Auto-Regressive Integrated Moving Average (ARIMA) are the major time-series based techniques. Artificial Neural Networks (ANN) approach is modelled similar to biological nerve cells. The time-series based models are generally associated with linear data; the neural network based models are generally associated with non-linear data structures (Saima *et al.*, 2011).

2.4.3.2 Assessment and comparison of modelling approaches

The persistence models are considered as the simplest modelling technique, and they surpass many other models in a very-short term time scale; however, the accuracy of these models decreases significantly in longer time scales (Lei *et al.*, 2009). El-Fouly *et al.* (2006) summarised that physical models were developed based on weather data. The models took many physical considerations including shelter from obstacles, local surface roughness, orography effect, speed up or down, etc. These models dealt with the prediction for 0–48 h ahead. The ANNs are trained using past data taken over a long time frame to learn the relationship between input data and output wind-speeds. ANNs have an input layer where historical data is fed for learning, hidden layer(s) and an output layer providing forecast results. Generally, ANNs outperform time-series models for almost all time-scales, although this is not necessarily universal (Soman *et al.*, 2010). When the number of training vectors is increased for the given ANN model, its performance is improved. More and Deo (2003) and Mohandes *et al.* (1998) compared ANN models with ARIMA models, and showed that ANN models perform better than ARIMA models.

2.4.4 Failure characteristics

The number and type of failures have a crucial importance on the selection of O&M fleet. This is because, the number of failures influence the number of visits, which need to be performed by the O&M vessels. The type of the failure is also important to identify the vessel, which then be allocated for that specific O&M task. In the following section, information associated with offshore wind turbine system, component failures, downtime, and existing failure analysis techniques is provided.

2.4.4.1 Wind turbine technology

Basically, wind spins turbine blades around a rotor that is connected to a shaft; however, rotational speed of the shaft may not be sufficient to generate power from generator; therefore a gearbox is generally installed between the rotor and the generator to increase the rotating speed. There are also direct-drive concepts (e.g., Enercon machines) available in the market, in which machine rotor is connected directly to low-speed generator (Polinder *et al.*, 2005). The produced power is transmitted through offshore subsea cables to onshore stations for generic usage. Although the principle of producing power via wind turbines is very simple, the entire process comprises significant number of components, both in terms of structure, which keeps the turbine at a certain height/location and equipment, which are utilised in power production and transmission.

- Turbine components

A typical wind turbine comprises of 8,000 different components, which can be categorised according to the tasks they are related to (EWEA, 2009). A commercial offshore wind turbine consists of a foundation, transition piece, tower, nacelle and blades. All the power production units are located in the nacelle in order to protect them from extreme weather conditions (Figure 24). In this section, structural/mechanical and electrical composition of offshore wind turbines are explained in details.

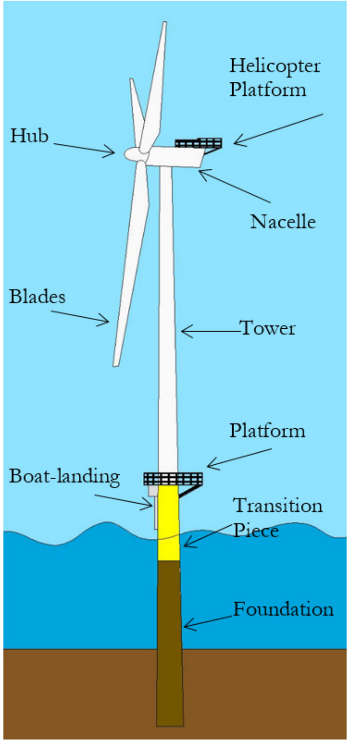

Figure 24: Conventional offshore wind turbineadapted from Tetra Tech EC INC. *et al.* (2010)

Foundation

Foundation is the supporting structure that keeps the wind turbine tower and other components above sea surface. The major foundation types are;

- *Monopile foundation*, which is simple tubular structures, is commonly used in water depths up to 20-25 m with the intention of keeping the diameter and mass of structures in effective levels (Schaumann and Böker, 2005). Monopile foundation can be fitted either by vibrating into or drilling into the seabed.
- *Gravity-based foundation* is the oldest available foundation system that can be installed in water depths up 10 m (Singh and Mistri, 2010). Gravity-based foundation is not drilled into the seabed. Instead, it is stabilised by adding extra sand, concrete, rock or olivine inside the foundation.
- *Suction caissons foundation* is installed through creating negative pressure inside the caisson in order to penetrate the caisson into the ground. The installation process requires relatively light-duty equipment and shorter time than traditional technologies, which lead a reduction in the overall capital costs of the projects (Byrne and Houlsby, 2006). Bakmar (2009) reported that steel required for the

fabrication of suction caissons foundation is relatively low; however, these structures are more complicated and can only be used in certain types of soil.

- *Tripod foundation* consists of main tubular structure supported by joint sections, which gives tripod foundations a larger resistance against overturning. Although offshore oil and gas industry has practical experience on tripod foundations up to 500 m depths, this type can be utilised often in North Seas between 30 m and 60 m water depths (Liwei and Jianxing, 2010).
- *Jacket foundation* is constructed from generally three or four main legs connected with intermediate braces. The origin of jacket foundation is oil and gas industry; therefore, the design loads of jacket foundation have to be investigated diversely due to the fact that loads associated with wind account for 60% of the entire fatigue damage of these underwater structures (Dong *et al.*, 2012).
- *Floating foundation* is designed with the purpose of preventing excessive material usage and eventually profitability decrease due to moving deeper areas. Floating foundation, which is secured via catenary wires, mooring lines or tension legs, is the most feasible solution in water depths more than 60 m (Tetra Tech EC INC. *et al.*, 2010). The main characteristic of floating wind turbine is the weight of installation has to be relatively light to float and heavy enough to stabilise upright position. Ballast stabilised, mooring line stabilised and buoyancy stabilised foundations are 3 major underwater structures in order to categorise the floating foundations according to static stability principles (Singh and Mistri, 2010).

Transition piece

Transition piece is the intermediate structure between the foundation and the tower, which has three main tasks; providing a flange for the tower connection, eliminating foundation misalignments, and supporting ladders, handrails and boat landing platforms.

Tower

Tower is the component that keeps the nacelle at a certain height. They are generally transported in 2 pieces due to the land transport limitations. Concrete, tubular and lattice towers are the major tower types, which are commonly installed in the commercial offshore wind farms.

Hub

Hub is the linking cast iron component, which connects blades to low-speed shaft inside the nacelle. Pitching mechanism is also located in hub in order to adjust the wind power capture capacity.

Blades

Blades are the largest and longest rotating component of a wind turbine. There are one-blade and two-blade designs for onshore wind farms; however, these designs are not well accepted in the offshore environment. Actually, one-blade and two-blade designs have better efficiency than three-blade designs; on the other hand, they have stability and noise issues due to higher rotational speed to yield the same energy output. The complexity of the design is another issue that creates difficulty in penetrating the offshore market.

Due to their size and weight of the blades, fibre-reinforced polymer composite materials are widely used in blade manufacturing. Blades directly expose to loads generated by wind and gravity in the lifecycle of a wind turbine. Increase in weight of a blade results in larger loads on rotor input shaft and bearings, subsequently yawing and pitching mechanisms; therefore, innovative material solutions, which can decrease weight/size ratio, can influence the turbine development significantly.

Nacelle

Nacelle is the box shaped structure that accommodates all the production and mechanical supporting units inside (Figure 25). Nacelle is connected to tower in vertical direction and also connected to hub in horizontal direction. The major components in a nacelle are;

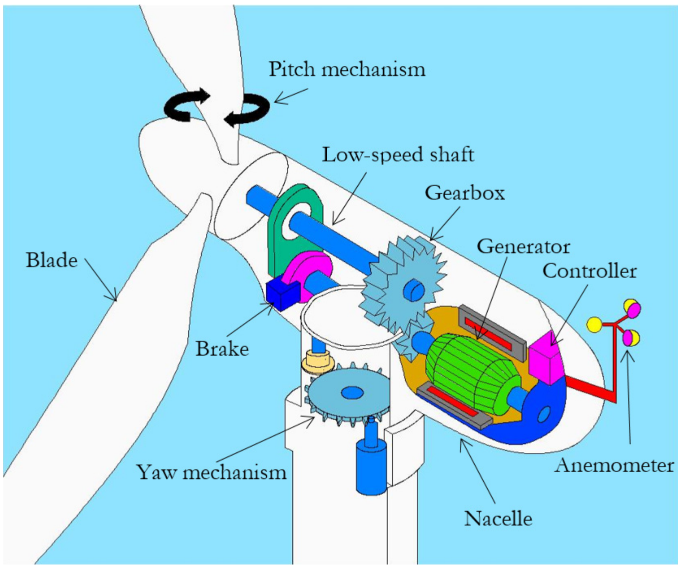

Figure 25: Internal view of a nacelleadapted from Ragheb (2014)

- Gearbox is intermediate element between generator and rotor. The purpose of a gearbox is converting slow rotating, high torque power, which is the output of a wind turbine rotor into high speed, low torque power, which is the input of a generator.
- Low-speed shaft is the main shaft that connects rotor and gearbox in order to transfer the rotational force.
- Yaw system is the mechanism which rotates the nacelle according to wind direction.
- Brake system is required when a maintenance activity is performed or wind speed is below/above the power production limits. In these circumstances, this turbine has to be kept in a fixed position in order to prevent damage to either technicians or turbine components. This is achieved through a brake system, which is similar to the disk brakes in cars.
- Transformer converts the electrical energy into alternative voltage levels with the help of mutual induction between two windings. Transformer is the key component to transfer electricity in long distances without excessive loss.
- Electrical power converter is widely used to reduce the inrush current in fixed speed system start-ups, as well as to control the speed and torque of generators in variable speed systems (Wu *et al.*, 2011).
- Generator is the main component which converts mechanical energy to electrical energy. As Zhaoqiang *et al.* (2011) investigated, within the operational offshore wind farms, the most dominant generator type is doubly-fed induction generator (49.2%) which is followed by squirrel cage induction generator (32.9%) and permanent magnet synchronous generator (11.8%). Basically,
    - Doubly-fed induction generator (DFIG) has stator which is connected directly with the grid and have rotor that is fed by a voltage or current source inverter to achieve variable speed operation. The ability to provide constant voltage-frequency from variable operational speeds and to operate in blustery weather conditions makes DFIG dominant in offshore wind industry (Tazil *et al.*, 2010, Lab-Volt, 2011, Umashankar *et al.*, 2011).
    - Squirrel cage induction generator (SCIG) is directly connected to Alternating Current (AC) grid that result in simpler structure and lower initial, operational

and maintenance costs than other types. In 2011, SCIG accounted for 80% of the installed offshore wind turbines in European seas (Madariaga *et al.*, 2012).

- Permanent magnet synchronous generator (PMSG) has rotors that are magnetised by permanent magnets. This generator does not require gearbox which creates an opportunity to decrease the nacelle weight and to improve the total availability of wind turbine (Brandao *et al.*, 2008). One particular characteristic of PMSG is the high efficiency ratings relative to other types, in medium and low speed operational conditions (Zhaoqiang *et al.*, 2011).

Grid connection and cables

Grid structure and electrical transmission of the offshore wind power can be divided into internal collection systems (inter-array cables) and external transmission systems (export cables). Internal collection systems can be designed either string or star configuration. In any case, substations, which transform power from 33,000 volts to 150,000 volts, are always utilised between internal collection and external transmission systems in order to adjust the voltage for further transportation to onshore stations (Bresesti *et al.*, 2007, Horan, 2012).

External transmission systems are high voltage cables and associated equipment, which transfer electricity from substation to onshore stations. Although AC and Direct Current (DC) cables can be used in cabling operations, AC cables are dominant in the commercial market due to their advantages in the short distance applications. Despite the fact that DC cable are cheaper alternative to AC cables due to the level of insulation required, extra equipment and overhead costs make DC cables more expensive solution to the electrical transmission (Wright *et al.*, 2002). According to Ackermann (2002), DC cables can be beneficial for wind farms with a minimum rating of 350 MW or with a minimum distance of 40 km to shore.

2.4.4.2 Failures and associated downtime

Turbine failures are classified depending on repair cost and required time for the repair. Minor failures occur frequently but lead to shorter downtime and the cost of repairs are relatively cheaper; however, numerous minor failures cause longer downtime, and due to complicated access the duration of this downtime increases. Conversely, major failures occur infrequently but lead to longer downtime and the cost of repairs is expensive. In this respect, Faulstich *et al.* (2011) studied the failure rates of wind turbine components proved that minor failures account for 75% of all failures. Spahic *et al.* (2009) showed that generators are the main cause of power systems unavailability. Haitao *et al.* (2009) analysed statistical failure rates and eventually recommended that the performance of gearbox has to be upgraded in order to improve the system availability. Tavner *et al.* (2007) analysed failure data of different offshore wind farms and indicated that the repair of mechanical subassembly failures is time consuming and costly, despite the fact that electrical control or system subassemblies have the highest failure rates. Rademakers *et al.* (2003) showed that blade, generator, and gearbox failures contribute over 75% to the overall cost and downtime. Ronsten (2009) reported that average of energy production losses, excluding manual stops during 205 turbine days, is more than four times higher in the wintertime compared to those in the summer time. El-Thalji *et al.* (2009) showed that the winter downtime is larger than other seasons' downtime.

2.4.4.3 Existing reliability calculation methods

Reliability calculations can be performed by analytical methods and Monte-Carlo simulations (Billinton and Allan, 1996). In analytical methods, reliability is evaluated by a mathematical model; Monte-Carlo methods simulate the actual process considering the random behaviour of the failures (Allan and Billinton, 1988). Monte-Carlo simulations provide a good understanding about the design and potential improvements of the analysed system (Wen *et al.*, 2009). Bussel and Zaaijer (2001) utilised Monte-Carlo simulations to investigate reliability aspects of offshore wind farms. For complicated system structure, Monte-Carlo simulations are more valuable than analytical calculations (Windebank, 1983). Monte-Carlo simulations also have a better structure to model multi-accidentals situations (multiple failures occur at the same time) than analytical models (Zhang *et al.*, 2011).

With respect to coverage areas of the reliability analysis, two main approaches are established in the failure characteristic and reliability investigation of offshore wind turbines. Whilst some of the studies investigated only a limited number of components or a single system in detail; such as generator system, grid connection, transmission (Brown and Taylor, 1999, Bertling *et al.*, 2005, Underbrink *et al.*, 2006, Arifujjaman *et al.*, 2009); other studies focused on the entire wind farm composition (Faulstich *et al.*, 2009, Spinato *et al.*, 2009), but missed some critical issues such as influence of individual failures on day-to-day operations. Arifujjaman *et al.* (2009) compared reliability performance of different power system configurations. Similarly, Negra *et al.* (2007) investigated power system failures. Brown and Taylor (1999) investigated the influence of different substation configurations on the overall system reliability. Reliability of grid connection for offshore wind farms is inspected by Underbrink *et al.* (2006). Gearbox failures are investigated by Smolders *et al.* (2010) and Feng *et al.* (2013).

Utne (2010) discussed the maintenance strategies for deep-sea offshore wind farms and also indicated that the existing models consider single units and single component systems. Although these research studies considered theoretical solutions related to the reliability issues, none of them represent the real operational offshore environment. There are many theoretical models, however most of them are not applicable to the offshore wind industry (Utne, 2010). El-Thalji (2012) indicated that it is critical to utilise models and practices, which should be suitable for the real life application/scenarios in the actual operating environment.

2.5 Gaps in the existing literature

During operational life span of an offshore wind farm, major decisions associated with a large number of technical, operational and financial aspects have to be made. In this context, custom-built models/tools can be utilised in order to evaluate the commercial feasibility of alternative solutions and different strategies. All these alternatives have to be evaluated from a life cycle point of view in order to define the most favourable option; this induces the direct need for a quantitative decision support model (Hofmann, 2011).

There are limitations with the current portfolio of developed models. These models are not able demonstrate the influence of different operating strategies for the entire O&M fleet. Furthermore, additional climate parameters (i.e. wave period and duration daylight) are required to be modelled in order to present the operational limitations in a more comprehensive manner.

Another issue is that the offshore access related operations are generally overly simplified or modelled in a crude way. However, it is not possible to present offshore O&M activities without considering the environmental factors and the influence of these factors on the vessel operations. As explained in the previous sections, O&M activities cannot be performed without offshore access, and thus, it is necessary to consider vessel specific aspects and reaction time to the failures in the maintenance methodology. Different transportation systems such as Crew Transfer Vessel (CTV), and jack-up vessel are highly utilised within an offshore project lifecycle; however the influence of these transportation systems on the O&M lifecycle cost cannot be thoroughly considered from the previously mentioned models.

OEMs are generally contracted to perform the O&M activities within warranty period (~5 years). In this period, operators are generally responsible for providing O&M vessels when OEMs request them. As part of agreement, technicians and components are provided by OEMs; therefore, operators cannot take the control of the entire operations within warranty period. Furthermore, OEMs share limited information with operators. From failure/reliability point of view, the majority of the proposed models are not applicable to offshore wind industry. This is because, the theoretical information cannot be implemented to real cases by the operators, since they have limited information and control over the operations.

Although distance to O&M port cannot practically be changed in the operational environment, it is believed that distance is a key aspect, which affects the O&M decisions and fleet configuration in planning stage. However, the influence of distance to O&M port has not been quantified properly.

Given the contribution of O&M to Levelised Cost of Energy (LCOE), a better understanding about the usage of different transportation systems is required. From this, a favourable and cost-effective O&M fleet can be established. It is generally aimed to sustain the productivity at the highest level; however the financial consequences are generally neglected. In this context, a model is proposed in order to identify the most favourable O&M fleet, which brings highest operational and financial benefits.

2.6 Chapter summary

In this chapter, the review of the existing literature is presented. At the first stage, O&M terminology, which is used in the thesis, is introduced. Then, existing studies and tools associated with offshore wind O&M are presented. In this stage, it has been identified that there is major gap in the fleet selection process; therefore, the review is narrowed down to vessel associated aspects. Due to the fact that fleet selection is a very sophisticated process, a comprehensive review about all the major aspects *vessel* *specifications*, *financial aspects*, *environmental conditions*, and *failure characteristics* is provided. The assessment of these aspects provides better understanding about which aspects control the O&M and can potentially create a larger impact, if improvements can be done. By identifying the gaps in the existing studies, tools, and models, the OPEX model for offshore wind and the O&M fleet selection methodology is proposed and presented in the following chapter.

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3 Main aim and objectives

The main aim of the thesis is to develop an operational expenditure model for offshore wind farms and to identify optimum operation and maintenance fleet. This aim is achieved by utilising oceanographic data, properties of vessels & ports, and failure characteristics of offshore wind turbines. This thesis can assist offshore wind farm operators and developers to improve operability and accessibility of wind farms, enhance reliability of operations, improve certainty of decisions, and reduce cost of operations.

The objectives related to the above mentioned aim are given below:

1. Identify the gaps in the literature and issues in the offshore wind operation and maintenance sector. Perform a thorough critical review. Identify the focus of research, for which an improvement can create the largest impact on the operational phase of offshore wind farms.
2. Propose a methodology to address the focus of research identified, considering operating wind farms as well as forthcoming projects.
3. Demonstrate the application of the methodology and identify the key parameters that influence operational and financial decisions. Elaborate the decisions associated with the configuration of operation and maintenance fleets.
4. Validate the methodology and demonstrate the performance of the methodology under different circumstances.
5. Provide suggestions at both generic and detailed level on how to improve the reliability of the offshore wind O&M activities, define a favourable operation and maintenance fleet (size and operational capability) and reduce the wind farm operating costs.

4 Methodology and Modelling

4.1 Chapter outline

In the previous sections, existing maintenance approaches and the methodologies applied in the offshore wind farm industry are presented. The benefits and the drawbacks of these approaches and the potential improvement opportunities, which can reduce the O&M costs and increase the competitiveness of the industry, are also analysed. In order to achieve the research aim and objectives as described in Chapter 3 and to bring alternative solutions to the issues identified in Chapter 2, this chapter aims to present and discuss the development of the methodology. The introductory information related to the proposed methodology is provided in Section 4.2. The definitions of the methodology variables, assumptions, requirements, and inputs are presented in section 4.3. Thereafter, Section 4.4 demonstrates the analysis/calculation methods throughout the methodology; in addition, the relations and the interactions between these methods are demonstrated. Section 4.5 presents how the decision is made and introduces the additional outputs of the methodology. As a conclusion, the summary of this chapter is presented in Section 4.6.

4.2 Development of the proposed methodology

In this section, the proposed OPEX model and O&M fleet optimisation methodology for offshore wind farms is demonstrated with an attempt to synthesise and simulate following six major analysis/calculation blocks;

1) Climate generation block,
2) Vessel operability analysis and transit time calculation block,
3) Failure simulation block,
4) Repair simulation block,
5) Power calculation block,
6) Cost calculation block.

There are also seven input sections, which provide information for the analysis/calculation blocks in particular formats as illustrated in Figure 26. The blocks with dashed outline present the input sections, whilst the blocks with thick black outline present the analysis/calculation sections. The final decision is made according to the cost calculation block outputs.

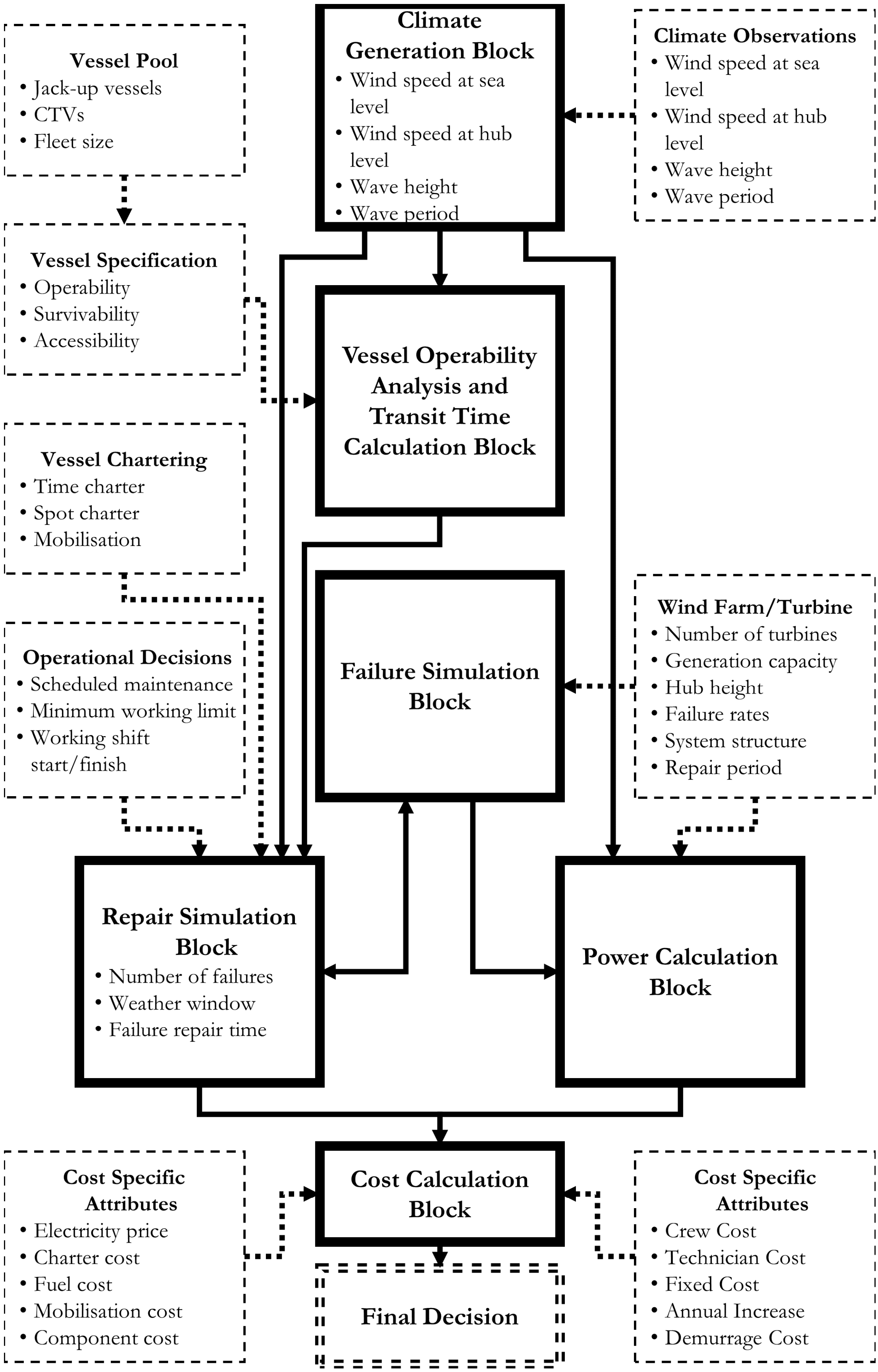

Figure 26: Proposed simulation methodology

In the simulation sequence, artificial climate datasets are generated from historical climate observations. Due to the fact that O&M activities are performed at different altitudes, historical wind speed observations are extrapolated to required altitudes prior to the artificial dataset generation. In order to eliminate the uncertainty of the climate on the simulation results, it is intended to generate diverse artificial datasets, which preserve the generic characteristics (distribution, weather window, correlation) of the original dataset. The outputs of the climate generation block influence the vessel operability analysis and transit time calculation block, repair simulation block, and power production block.

The vessel operability analysis and transit time calculations are performed considering the generated artificial climate datasets, the vessels in the vessel pool, and the specifications of these vessels. In this block, hull resistance calculations are performed at the first stage. Then, the speed loss due to waves is calculated for all the vessels in each scenario and the transit time calculations are performed by using the calculated achievable speed value. Furthermore, productive time and non-productive time of the O&M technicians are calculated on a daily basis. The outputs of the vessel operability analysis and the transit time calculation block influence the repair simulations block by providing the actual vessel accessibility and the actual daily working period information.

In order to identify the failures, time domain Monte-Carlo simulations are performed in the failure simulation block. In this context, turbine failures are dependent on the turbine component failure rates which are also time dependent as well as the configuration of the turbines. Therefore, the entire turbine failure rates are calculated from the individual turbine component failure rates considering whether the turbine has parallel or series or mixed configuration. Due to the fact that a failed turbine cannot fail again until the former failure is repaired, the failure simulation block also receives information from the repair simulation block.

In the repair simulation block, the actual O&M activities are simulated considering the failure time steps, number of simultaneous failures, type of vessels and the number of O&M technicians required for the repair activity, vessel availability, vessel operability, and the artificial climate datasets. When a failure is identified, a vessel is allocated for the actual O&M activity. After the O&M activity is completed, the time step that the turbine starts to function is identified. The failure simulation block is fed with the time step information and then, the failure rate of the failed component is reset while the failure rates of all the other components remain the same. The entire turbine failure rate is calculated again by using the updated component failure rates and additional Monte-Carlo simulations are performed by using the updated turbine failure rates. From power production point of view, the main output of the repair simulation block is the MTTR and Mean Time to Failure (MTTF) values for each individual turbine in the offshore wind farm. From operational point of view, the main outputs of the repair simulation block are vessel mobilisation, vessel utilisation, total vessel travel times, technician utilisation, and the number of turbine visits per day. These operational outputs provide initial information for the cost calculation block.

In the cost calculation block, all the outputs of the previous analysis/calculation blocks are synthesised with the cost specific attributes; and the final results are calculated to compare and identify the most cost effective scenario. The information regarding turbine downtime/uptime information is merged with the generated artificial wind speed at hub height values; and the wind farm power production values for each time step are calculated. The total revenue is calculated by multiplying the power production values and the unit electricity price. In addition, major cost attributes are calculated in order to identify the asset value of the O&M activities. The asset value denotes the remaining financial value when all the costs are subtracted from the total revenue.

The novel methodology eliminates the gaps in existing O&M models in the offshore wind industry by providing comprehensive analyses and selecting the most favourable O&M fleet. Optimisation of the O&M fleet in the thesis refers to the identification and selection of the most favourable O&M fleet, which brings financial and operational benefits. It should be highlighted that the developed model is not an optimisation tool. Instead, all the configurations are simulated and the best O&M fleet among pre-defined configurations is selected. It is a unique and integrated approach, in which climate (wind speed, wave height, and wave period), vessel operations, maintenance operations, and power calculations are performed in a single framework. The proposed approach brings better understanding especially on the daily operations and associated costs, which are generally neglected in the current practices. The ability to investigate different O&M vessels with different specifications provide offshore wind farm developers/operators with extensive support in order to define the most cost effective O&M fleet. Moreover, the detailed analysis performed for the jack-up operations demonstrate the importance of charter contract type on the total O&M cost. Another advantage of the developed methodology is the block structure. If more accurate analysis methods are developed in the future, the individual calculation blocks in the methodology can be updated/replaced without changing the entire methodology.

In the following sections, based on the industry end user requirements and literature survey of existing models, the simulation inputs; climate observations, vessel pool, vessel specifications, vessel chartering, cost specific attributes, and wind farm/turbine specific attributes including turbine component failure rates are introduced in the first place and the phases where these inputs are considered during the simulations are explained. Secondly, the major analysis/calculation blocks; climate generation, vessel availability, accessibility and operability analysis, failure simulation, repair simulation, power calculation, and cost calculation blocks are explained in detail to present the simulation logic.

4.3 Input sections

4.3.1 Climate observations

Climate is one of the most important measures, which influences the offshore wind O&M activities. Wind speed, wave height and wave period are major environmental constraints which do not only affect the journey specific issues, but also the electricity generation of the offshore wind farms. In a generic context, areas with stronger wind characteristics are more valuable for electricity generation. However, with regard to O&M activity, stronger wind is a constraint, similar to higher wave heights. Furthermore, stronger wind speeds have a negative effect on the failure characteristics of the wind turbine components (Arwade *et al.*, 2011).

In the proposed methodology, 'wind speed', 'wave height' and 'wave period' datasets are required to run the simulations (Table 5). It is intended to perform simulations in time domain format; therefore, the datasets also have to be in the time domain format. In this respect, datasets with higher resolution (1-hour or higher) increase the accuracy of the calculations and represent real operational environment with minimum data loss; since the intervals are smaller and the number of data points is larger in high resolution datasets, in comparison to the low resolution datasets. The 'resolution (frequency)' of the climate observations has to be identical for each individual dataset for consistency purposes (i.e. wind speed, wave height and wave period); because the analysis/calculations are performed for each time step within the simulation period.

The altitude of the wind speed observation point is also important for the calculation blocks; because, wind speed values have to be extrapolated to certain altitudes in the climate generation block in order to calculate the 'wind speed values at sea level' and 'the wind speed values at hub level'. In addition, the 'surface roughness' factor is required in the extrapolation stage. If a database is available with both wind speed values at sea level and hub level, extrapolation step is not performed; instead, the original observations are used. The units of the 'wind speed', 'wave height', 'wave period', and 'observation altitude' are m/s, m, s, and m, respectively. The 'surface roughness' factor is a constant without unit.

Datasets with a length of 1-year (at least) and without any gaps are employed in the simulations. However, it is beneficial to have larger datasets with good/bad weather years. It is also important for the demonstration of the seasonal (monthly) variations in the climate parameters. If a single year is used to feed the climate generation block with the related information, the climate can still be modelled and generated, but the crucial information may be overlooked due to lack of source data.

Table 5: Climate observation inputs

Input Name	Value Range	Unit
Wind speed	[0,∞)	m/s
Wave height	[0,∞)	m
Wave period	[0,∞)	$second$
Observation frequency	[0,∞)	$hour$
Observation altitude	[0,∞)	m
Surface roughness	[0,∞)	$-$

4.3.2 O&M vessel pool

Table 6 demonstrates the input names, range of values and the unit of the inputs for the vessel pool input section. It is envisaged that the vessel pool consists of two major O&M vessel types; the vessels for the minor maintenance activities and the vessels for the major maintenance activities. A jack-up vessel that has a self-propulsion system, and two CTV types (monohull and/or catamaran) can be defined for the analysis within the proposed methodology. Due to the fact that these vessels (jack-up and CTV) have different O&M

purposes to perform at the offshore wind farm, one jack-up vessel and at least one CTV have to be defined prior to the simulations. In this respect, an O&M fleet is assumed to be composed of those vessels to perform the repairs; but the composition may vary considering wind farm size, failure rates of the turbine components, climate conditions, and major cost attributes.

In the proposed methodology, it is also required to define the 'minimum CTV fleet size' value and the 'maximum CTV fleet size' value in order to create different scenarios. Moreover, there are two different charter agreements for the specified jack-up vessel; therefore, two different scenarios are created for the CTV fleet; the first case is when the jack-up vessel is under voyage charter contract (short-term), and second case is when the jack-up vessel is under bareboat charter contract (long-term). If only one 'CTV type' is defined, the simulations are run for all the CTV fleet size values ranging from the minimum fleet size value to the maximum CTV fleet size value. If two or more 'CTV types' are defined, the simulations are run for all the CTV fleet size value combinations, which again range from the minimum fleet size value to the maximum CTV fleet size value. The 'minimum/maximum fleet size' values and the 'number of CTV types' that are analysed, have to be defined carefully; since the number of combinations and essentially the computation time may increase significantly (Table 7). In order to explain the scenario generation, the first column of Table 7 is demonstrated in Figure 27. There are 3 CTV types, the 'minimum fleet size' value is 2, and the 'maximum fleet size' value is 7. In addition, there are 2 jack-up charter types. Through these inputs, n number of scenarios are generated, and these scenarios run for both jack-up charter types in order to preserve the relations between minor and major O&M activities. The number of CTVs, the maximum fleet size, and the maximum fleet size values are defined as positive integers.

Table 6: Vessel pool inputs

Input Name	Value Range	Unit
Number of jack-up vessels	1	–
Number of CTV types	[1, ∞)	–
Minimum fleet size	[1, ∞)	–
Maximum fleet size	[1, ∞)	–

Table 7: Examples for the number of CTV fleet size combinations

Input Name	Input Value			
Number of CTV types	3	3	5	5
Minimum fleet size	2	2	2	5
Maximum fleet size	7	10	10	10
Number of scenarios	232(116*2)	564(282*2)	5994(2997*2)	5754(2877*2)

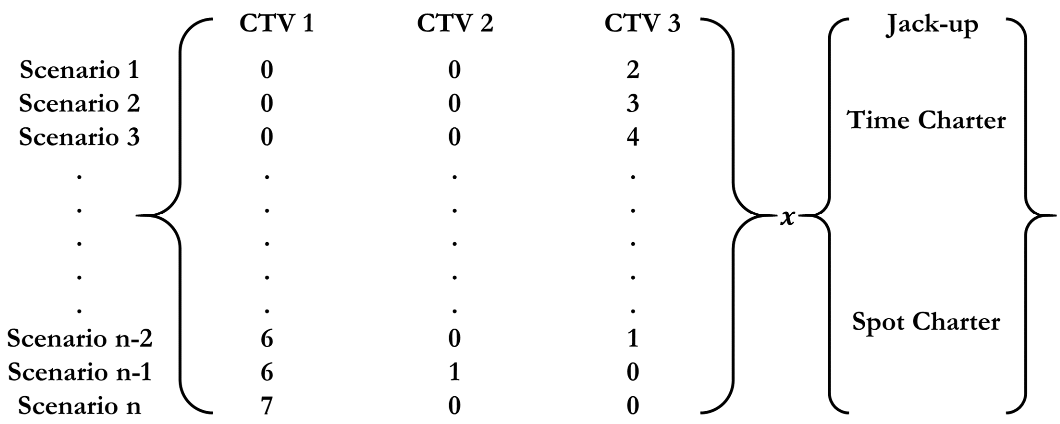

Figure 27: Sample scenario generation

4.3.3 Vessel specification

After identifying the vessels that will be analysed in the simulations, the next step is defining the specifications (i.e. hull parameters, operability, accessibility, and survivability limitations) of these vessels. With regard to jack-up vessel, 'operability and survivability limitations' are governed by the wind speed and the wave height values (Table 8). The O&M activities are limited by the vessel operability; while, the vessel survivability limits the voyage such as a storm, which can cause vessel capsizing or sinking. If the climate observations are higher than the vessel operability limits, the vessel can stay at the wind farm and wait until the conditions are met for the O&M activity. However, if the climate observations are higher than the vessel survivability limits, the vessel cannot stay at the wind farm. In this case, the vessel leaves the offshore wind farm site in order to find a safe location to anchor.

It is assumed that the jack-up vessel is capable enough to perform all the specified major O&M activities in terms of crane capacity, hook height, and operational water depth. Jack-up vessel survivability is modelled considering wind speed values at sea level and wave height values. Jack-up vessel operability is modelled in three sequential steps; jacking up, actual repair, and lastly jacking down. 'Wind speed at sea level' and 'wave height' are taken into account for jacking up/down operations. When the jack-up vessel completes the jack-up operations, the actual repair operations are dependent on the 'wind speed values at hub height'; considering the vessel survivability is the major prerequisite to start/perform the O&M activity. m/s for wind speed and m for wave height are the units of the 'operability and the survivability limitations' for jack-up vessels.

From operational cost point of view, ‘daily fuel consumption in port’, ‘daily fuel consumption in operation’, ‘vessel age’, ‘number of crew’, ‘number of O&M technicians’, and ‘size of management team’ are crucial to represent the current O&M activities. The ‘vessel age’ value is required to define the dry-docking cost, in the case that a bareboat charter contract is signed for the jack-up vessel. The dry-docking model is based on the survey requirements report prepared by DNV (2011). The survey rules show that two bottom surveys are required during each five-year and the interval between two bottom-surveys cannot exceed 36 months. It is also mentioned that the first bottom survey should be carried out when the vessel is exceeding 15 years of age. These inputs do not influence the operational simulation logic, but the costs associated with them significantly affect the decision. Due to the fact that the costs associated with jack-up vessel are directly dependent on the charter agreement, particular costs are considered in particular scenarios. The details regarding costs are given in cost specific attributes section and cost calculation block.

Table 8: Jack-up vessel specification inputs

Input Name	Type	Value Range	Unit
Wind speed at sea level	Jacking	[0,∞)	m/s
Wave height	Jacking	[0,∞)	m
Wind speed at hub level	Operational	[0,∞)	m/s
Wind speed at sea level	Survival	[0,∞)	m/s
Wave height	Survival	[0,∞)	m
Daily fuel consumption in port	Cost	[0,∞)	$tons$
Daily fuel consumption in operation	Cost	[0,∞)	$tons$
Jack-up/down time	Operational	[0,∞)	$m/hour$
Vessel age	Cost	[0,∞)	$year$
Number of crew	Cost	[0,∞)	$-$
Number of O&M technicians	Operational-Cost	[0,∞)	$-$
Size of management team	Cost	[0,∞)	$-$

Due to the fact that CTVs are employed on a daily basis, these operations are modelled in a more comprehensive way. Length, breadth, draught, displacement, operational speed, installed power of the CTVs are required to perform resistance and speed loss calculations (Table 9). The operational limitations of the CTVs comprise of the ‘maximum operational wave height’ and the ‘maximum operational wind speed’. ‘Fuel consumption at operating speed’, ‘O&M technician capacity’, ‘number of crew on-board’ are also required to perform simulations and provide cost calculation block with information. The units of the ‘CTV length’, ‘breadth’, ‘draught’, ‘displacement’, ‘operational speed’, ‘installed power', 'maximum operational wave height', 'maximum operational wind speed', and 'fuel consumption at operating speed' are m, m, m, $tons$, $knot$, kW, m, m/s, m^3/h, respectively. The 'O&M technician capacity' and the 'number of crew on-board' can be defined by any positive integer. In the simulations, different input values can be defined for different CTV types; so alternative CTV fleets with different types/sizes/operational limitations can be configured.

Table 9: CTV specification inputs

Input Name	Type	Value Range	Unit
Vessel type	Operational	Monohull-Catamaran	$-$
Length	Operational	[0,∞)	m
Breadth	Operational	[0,∞)	m
Draught	Operational	[0,∞)	m
Displacement	Operational	[0,∞)	$tons$
Operational speed	Operational	[0,∞)	$knot$
Installed power	Operational	[0,∞)	kW
Wave height	Operational	[0,∞)	m
Wind speed	Operational	[0,∞)	m/s
Fuel consumption	Cost	[0,∞)	m^3/h
Technician capacity	Operational- Cost	[0,∞)	$-$
Number of crew	Cost	[0,∞)	$-$

4.3.4 Operational decisions

The inputs associated with the actual working conditions are defined in the operational decisions inputs section. Due to the fact that the daily charter rates of the jack-up vessels are significantly high regardless of the contract type; it is assumed that the O&M technicians work on a 3-shift pattern (the first shift 8am-4pm, the second shift 4pm-12pm, the third shift 12pm-8am), so the O&M tasks can be completed as quickly as possible. Therefore, the O&M activities for major type failures continue without any break. It is also assumed that the specified jack-up vessel has enough supply to complete the repairs without leaving the offshore wind farm.

There are additional decisions that have to be made for the CTV operations (Table 10). When a CTV is allocated for a failure, the transit time for that specific CTV is calculated in transit time block. When the CTV is reached to the turbine, the O&M technicians have to be transferred from the CTV to the turbine, and the technicians need to carry or transfer (by nacelle crane) all the equipment required to the nacelle level before starting to work. The time required to transfer the O&M technicians and equipment from a CTV to nacelle is modelled as 'work start delay' value. After the O&M technicians are transferred from the CTV to the turbine, the same CTV may visit other turbines for other O&M tasks. In this case, inter-transit time between turbines is required to calculate the delay for subsequent O&M tasks.

As identified in the literature review chapter, corrective and preventive maintenance approaches dominate the offshore wind O&M activities; therefore, these maintenance approaches are considered in the methodology. The corrective maintenance tasks are performed after the failures; so these tasks are only dependent on the failure frequency. However, turbines require preventive maintenance on an annual basis; therefore preventive maintenance per year per turbine has to be defined prior to the simulations. The O&M technicians for the CTV associated maintenance tasks are assumed to work 12 hours in a day. Due to the fact that there are variations in climate conditions throughout a day, the start hour of the CTV shift is required to perform the transit time calculations.

Theoretically (with unlimited resources), one CTV can operate for unlimited number of turbines in a single shift; however, this situation does not represent reality due to safety reasons. In case of emergency, the CTV should be able to sail back to the turbine and transfer O&M technicians from turbine to the CTV immediately; therefore, a value is defined for limiting the number of visits that can be done by one CTV in a single shift. As in the number of visits for CTVs, theoretically the allocation of more technicians will lead to the completion of the repair in a shorter time period, however in reality there is a maximum value, above which an increase in the number of technicians will not bring an advantage on the repair time. Therefore, two values are defined in order to represent the number of technicians that will be allocated in two conditions;

- regular number of technicians that will be allocated in normal repair conditions
- maximum number of technicians that will be allocated in order to reduce the repair time and/or complete the repair in a single shift

The maximum number of technicians are allocated to a turbine unless the repair can be completed in a single shift by the regular number of technicians.

In addition to the environmental constraints, there might be circumstances which the distance that is logged in sequential time steps might not be sufficient enough in order to make the journey cost effective. Additionally, there might be some cases that the time spent on the journey might be longer than the time will be spent for the actual O&M

activity. Therefore, a 'minimum working limit' has to be defined for making a working shift as acceptable and cost effective. The 'minimum working limit' will create extra constraint for the transit model. Although, the maximum weather window value is more than the summation of the 'productive time' and the 'travel time', if the 'productive time' value for that day is less than 'minimum working limit', 'productive time' and the 'travel time' values will be set to zero and 'idle time' will be set to the shift length, which indicates that the CTVs will not sail in this repair day, because cost of the journey will be higher than the benefits that will be gained from the O&M activity.

Table 10: Operational decision inputs

Input Name	Type	Value Range	Unit
Inter-transit time	Operational	[0,∞)	min
Maximum visit for a CTV	Operational	[1,∞)	$-$
Regular number of technicians	Operational	[1,CTV Capacity]	$-$
Maximum number of technicians	Operational	[1,CTV Capacity]	$-$
Preventive maintenance	Operational	[0,∞)	$h/year$
Minimum working limit	Operational	[0,∞)	h
Shift start	Operational	[1,12]	$hh:mm$

4.3.5 Vessel chartering

4.3.5.1 CTV chartering

The charter of the CTV fleet is modelled assuming the fact that a continuous bareboat charter option with a 1-year period is selected for the CTV charter. In this context, the offshore wind farm operator is responsible for the daily charter payments of the specified CTV fleet, and all the other operating costs such as fuel cost, fixed costs and crew costs. When the charter period is completed, it is theoretically extended for another 1-year, but all the costs (charter rate and other operating costs) are increased by defined increment values. These increment values are modelled separately for each cost attribute; therefore, individual increment values can be defined for the charter rates and each operating cost attribute.

4.3.5.2 Jack-up chartering

Daily charter rates for jack-up vessels are extremely high compared to the CTV charter rates, which can change significantly depending on the charter agreement. In this respect, the jack-up chartering requires a more comprehensive approach than CTV chartering. This is because, the number of vessels is significantly low compared to the number of CTVs in the offshore wind market and therefore, variations in the daily charter rates due to seasonal availability are experienced and also expected in the future. In this context, accurate charter rate datasets are required to calculate the charter cost of jack-up vessels; however, there are a number of attributes that negatively influence the data gathering process;

- Lack of offshore wind data,
- The confidentiality of available data among all the offshore wind market stakeholders,
- The low number of purpose-built vessels for the offshore wind market,
- The impact of negotiations between vessel owners and charterers/operators,
- The potential vessel supply unavailability due to high demand from offshore oil and gas industry

In this respect, the shipping market in terms of the vessels employed and the relevant chartering options and accordingly rates are utilised in order to overcome these difficulties in the modelling.

- Identification of jack-up vessel charter rates

The CAPEX, which is the capital invested by a company to acquire or upgrade fixed, physical, non-consumable assets, is proportional to the capabilities of the vessel. When the influence of the economic variations associated with the new building market is neglected, vessels with higher speed, better lifting capability (hook height, lifting tonnage, etc.), deeper operability and longer durability in harsher conditions have higher CAPEX values. With regard to charter rates, it was also anticipated that the vessels with better structural condition and with the ability to perform the O&M activities more efficiently in harsher conditions, would have higher daily charter costs. Therefore, the relationship between the CAPEX values of different vessels and associated charter rates for different periods is employed to establish the estimation of the daily charter rates for jack-up vessels.

In order to collect CAPEX and charter rate values for different vessel types (bulk carrier and tanker), Astrup Fearnley (2014) database, which includes the shipping market charter rates for different types of vessels is taken into account. Although the offshore wind vessel market does not explicitly operate in the same way as the shipping vessel market, these vessels are employed due to parallel trends over similar trading/chartering scenarios for specific chartering periods. In this context, historical charter rates (from 2004 to 2010) for Capsize, Panamax, Handymax type bulk carriers and VLCC, Suezmax, Aframax, Product type tankers are examined. In this period, shipping market experienced peak and bottom figures in terms of both CAPEX and charter rates. Therefore, the calculations through the analysis of these rates are beneficial to capture regular charter rates instead of charter rates under extreme economic circumstances.

The steps below are followed in the jack-up charter rate calculations;

Identifying the relation between CAPEX and charter rates:

All the charter rates (spot charter and time charter) and CAPEX values for the specified vessel are gathered from the Astrup Fearnley (2014) database. The historical CAPEX values are divided by the historical charter values that are observed at the same time period. Through these mathematical divisions, CAPEX/Spot and CAPEX/Time-Charter values are calculated for each vessel type.

$$\text{CAPEX/Spot Value} = \frac{CAPEX}{Spot\ charter\ rate} \qquad \text{Equation 1}$$

$$\text{CAPEX/Time Charter Value} = \frac{CAPEX}{Time - charter\ rate} \qquad \text{Equation 2}$$

Representing the data by distributions:

The CAPEX/Spot and CAPEX/Time-Charter values are fit into major continuous probability density distributions. In the proposed model, Beta, Birnbaum-Saunders, Exponential, Extreme Value, Gamma, Generalised Extreme Value, Inverse Gaussian, Logistic, Log-Logistic, Lognormal, Nakagami, Normal, Rayleigh, and Weibull distributions, which are explained in detail by O'Connor (2011), are investigated in order to identify the distribution that best represents the datasets.

Identifying the distribution that best represents the datasets:

In this respect, the data points have to be fitted to the distributions as stated above and then these fits are compared to what extend they represent the original observations. However, model comparison is a difficult task. The reason is that more complex distribution models will always fit the data better (Mackay, 1992). On the other hand, these models also cause over-fitting due to the extra variables, which leads to exaggeration of the minor fluctuations in the observations. Under-fitted probability distributions also have to be avoided; because, they do not represent the observations due to lack of details in the models. Both over-fitting and under-fitting models can lead to poor predictive ability; therefore they have to be avoided (McQuarrie and Tsai, 1998, Van der Aalst *et al.*, 2010).

Information criteria are utilised in the comparison of different distribution models for the same data. Essentially, information criteria are likelihood-based measures of model fit that include a penalty for complexity (the number of parameters) which penalise distributions with greater number of parameters, and help to avoid the over-fitting issues. A likelihood function gives the probability of observing the data given a certain set of model parameters. The commonly used information criteria are as follows:

- Akaike Information Criterion (AIC), which was developed by Akaike (1974), is an estimate of a constant plus the relative distance between the unknown true likelihood function of the data and the fitted likelihood function of the model, so that a lower AIC means a model is considered to be closer to the truth. AIC, is derived as an estimator of the expected Kullback discrepancy between the true model and fitted candidate model through minimising the expected residual of some future observation. AIC has the form;

  $$AIC = -2\ ln(maximum\ likelihood) + 2m \qquad \text{Equation 3}$$

  where likelihood is the probability of the data given a model and m is the number of parameters in the chosen model.

- Bayesian Information Criterion (BIC), which was developed by Schwarz (1978), is also known as Schwarz Information Criterion. BIC is an estimate of a function of the posterior probability of a model being true, under a certain Bayesian setup, so that a lower BIC means that a model is considered to be more likely to be the true model. BIC has a higher penalty for over-fitting compared with AIC. The BIC for a given model is given below;

  $$BIC = -2\ ln(maximum\ likelihood) + m\ ln(n) \qquad \text{Equation 4}$$

  where m is the number of parameters in the chosen model and n is the number of observations.

- Hurvich and Tsai (1989) introduced a corrected version of AIC which takes the penalty term for AIC and multiplies it by a correction factor. Like AIC, Corrected Akaike Information Criterion (AICC) is also derived as an estimator of the expected Kullback discrepancy between the true model and fitted candidate model.

$$AICC = -2ln(maximum\ likelihood) + \frac{(2m(m+1))}{(n-m-1)} \qquad \text{Equation 5}$$

where m is the number of parameters in the chosen model and n is the number of observations.

According to Kuha (2004), AIC and BIC are the most commonly used model selection criteria. Due to BIC's computational simplicity and effective performance in many modelling frameworks, it is widely used tools in the models selection tasks (Neath and Cavanaugh, 1997). However, BIC is not recommended when the sample sizes are small due to the large amount of uncertainty (Burnham and Anderson, 2002). Burnham and Anderson (2002) recommended that using AICC is beneficial in the model selection when the sample sizes are small and the sample elements are (nearly) independent. Hurvich and Tsai (1989) compared 8 different model selection criteria for small sample sizes, and proved that the AICC provides the best selection amongst all criteria studied; while other criteria tend to over-fit the data. In addition, Cavanaugh (1997) recommended utilising AICC in small sample size applications. Based on the finding from the literature, AICC is selected to compare the models.

Generating daily charter rates for jack-up vessels

In the previous steps, the best distributions are identified for each vessel type. However, it is also important to identify the vessel type that represents the jack-up vessel charter rates better than the other vessel types. If the CAPEX/Spot and CAPEX/Time-Charter values are significantly low or high, the generated jack-up charter rates do not present the actual charter rates in the current offshore wind market. In this respect, daily charter rates (spot rate and time charter) for jack-up vessels are generated randomly by using the jack-up vessel CAPEX values and the distribution identified in the previous step. However, the distribution characteristics can increase or decrease the probability of observing particular charter rates. Although the charter rates are generated randomly, the distributions control the randomness. Generated jack-up vessel charter rates are compared with real cases so the vessel with optimum CAPEX/Spot and CAPEX/Time-Charter ratios is selected for the jack-up charter rate generation.

Seasonality

In addition to what has been discussed so far, it is well known in industry that the charter rates of jack-up vessels vary considerably depending on the season in which the operators/developers intend to hire the vessels. As harsh weather conditions restrict the maintenance operations in the offshore environment; thus decreasing the demand, it is expected that the charter rate for jack-up vessels will be at the lowest level during winter months. Furthermore, power ratings are higher in winter compared to summer, and there is a low probability that the weather conditions can cease maintenance operations in summer. In addition, monthly capacity factors show lower trends in summer seasons, which also decrease the power generation. Due to these reasons, operators plan their maintenance activities in summer seasons, which increase demand for offshore wind vessels.

In this respect, the scarcity of data and the immaturity of the offshore renewable market do not provide an accurate sample size of charter rate data. In order to overcome this obstacle, the daily charter rates of the selected vessel type are employed in order to address the seasonality effect. It is assumed that only spot market charter rates have the variation due to seasonality; therefore CAPEX/Spot values of the selected vessel type are divided into two groups. The first group consist of the highest half of the CAPEX/Spot values; on the contrary, the second group consist of the lowest half of the CAPEX/Spot values. If the CAPEX/Spot values are relatively higher, the jack-up charter rates generated by these values will be lower; if the CAPEX/Spot values are relatively lower, the jack-up charter rates generated by these values will be higher. Therefore, the distribution of the first group is employed to generate spot market charter rates in winter, and the distribution of the second group is employed to generated spot market charter rates in summer.

4.3.6 Wind farm/turbine specific attributes

Table 11 specifies the inputs associated with wind farm and wind turbines. The number of turbines in the offshore wind farm is one of the most crucial information for the simulation logic. The power production and the number of simultaneous failures are directly related to the number of turbines value. The power generation is also related to the generation capacity of the turbines. If the generation capacity becomes larger, the revenue loss per unit time becomes more significant.

Due to the fact that CTV operations are performed on a daily basis, the distance from a specific port to the offshore wind farm is also an important measure for the definition of O&M fleet. If the distance is relatively long, the number of O&M activities performed by a single CTV reduces; therefore, the longer distance between the port and the offshore wind farm results in larger O&M fleet in order to minimise the reaction time to the turbine failures. As explained in the climate observations, the wind speed values are extrapolated to hub level. Furthermore, the jack-up operations are also limited by the wind speed values at hub level. These measures require hub height in order to extrapolate wind speed, and eventually calculate power production and simulation jack-up operations more accurately. For the calculation of power production, the power curve of the turbines, cut in speed, and cut out speed values are required.

The failure simulations are performed on each turbine; therefore, the turbine component failure rates and the turbine system structure are critical for the failure analysis. In the repair simulation block, the repair period for each failure type is also required to identify the time spent for the actual O&M activity. The existing methodologies assume that all the components are at the same age. This may not be the case if an operating offshore wind farm will be analysed. Therefore, more accurate calculations can be performed, if the age of the components is considered within the methodology. This information is provided in a matrix format, which the rows represent the name of the turbine components (Figure 28). The technical lifetime of the wind farm components is approximately 20 years (Wagner *et al.*, 2011, Laura and Vicente, 2014); therefore, there are 20 columns in the matrix, so the number of components within 1 year age interval can be defined and employed in the failure simulation block. The method for how the component age matrix is employed in the simulation is explained in the failure simulation block.

Table 11: Wind farm/turbine inputs

Input Name	Type	Value Range	Unit
Hub height	Power	[0,∞)	m
Number of components	Structure	[1,∞)	$-$
Component failure rates	Failure	(0,∞)	$-$
Access type for failures	Operation	Jack-up or CTV	$-$
Cut in speed	Power	[0,∞)	m/s
Cut out speed	Power	[0,∞)	m/s
Power curve	Power	[0,∞)	$-$
Number of turbines	Power- Operation- Failure	[0,∞)	$-$
Repair time	Operation	[0,∞)	h
Age of components	Operation- Failure	[0,20]	$year$

Age of components

	0	1	2	3	4	5	6	……	17	18	19	20
Component 1	x_a	x_b	x_c	x_d	x_e	x_f	x_g	……	x_p	x_r	x_s	x_t
Component 2	y_a	y_b	y_c	y_d	y_e	y_f	y_g	……	y_p	y_r	y_s	y_t
Component 3	z_a	z_b	z_c	z_d	z_e	z_f	z_g	……	z_p	z_r	z_s	z_t
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Component n-2	t_a	t_b	t_c	t_d	t_e	t_f	t_g	……	t_p	t_r	t_s	t_t
Component n-1	p_a	p_b	p_c	p_d	p_e	p_f	p_g	……	p_p	p_r	p_s	p_t
Component n	r_a	r_b	r_c	r_d	r_e	r_f	r_g	……	r_p	r_r	r_s	r_t

Figure 28: Component age matrix

4.3.7 Cost specific attributes

Table 12-Table 16 present the cost attributes for each major input category. These inputs are required to calculate total revenue, total charter cost, total OEM cost, total fuel cost, total staff cost, total O&M cost, total revenue loss, total mobilisation cost, total dry-dock cost, and total fixed cost. The calculation logic related to the inputs in Table 12-14 are explained in cost calculation block. The inputs in Table 12 are required for the revenue calculations. The inputs in Table 13 are required for jack-up vessel specific cost attributes if the vessel is chartered from the spot market. The inputs in Table 14 are required for the calculation of jack-up vessel specific cost attributes if the vessel is charted for longer periods. The attributes in Table 15 are required for the cost calculation of CTV associated operations. The values in Table 16 are used for determining the Original Equipment Manufacturer (OEM) costs.

Table 12: Power production cost inputs

Input Name	Type	Value Range	Unit
Electricity price	Revenue	[0,∞)	$£/kW$
Annual increase	Revenue	[0,∞)	%

Table 13: Jack-up spot market cost inputs

Input Name	Type	Value Range	Unit
Winter charter rate	Charter cost	[0,∞)	$£/day$
Summer charter rate	Charter cost	[0,∞)	$£/day$
Winter demurrage	Charter cost	[0,∞)	%
Summer demurrage	Charter cost	[0,∞)	%
Annual increase	Charter cost	[0,∞)	%
Mobilisation cost	Mobilisation cost	[0,∞)	£
Annual increase	Mobilisation cost	[0,∞)	%

Table 14: Jack-up time charter cost inputs

Input Name	Type	Value Range	Unit
Charter rate	Charter cost	[0,∞)	$£/day$
Annual increase	Charter cost	[0,∞)	%
Crew cost	Staff cost	[0,∞)	$£/pp$
Annual increase	Staff cost	[0,∞)	%
O&M technician cost	Staff cost	[0,∞)	$£/pp$
Annual increase	Staff cost	[0,∞)	%
Management team cost	Staff cost	[0,∞)	$£/pp$
Annual increase	Staff cost	[0,∞)	%
Dry-docking cost	Dry-dock cost	[0,∞)	$£/docking$
Annual increase	Dry-dock cost	[0,∞)	%
Fixed cost	Fixed cost	[0,∞)	$£/year$
Annual increase	Fixed cost	[0,∞)	%
Fuel cost	Fuel cost	[0,∞)	$£/m^3$
Annual increase	Fuel cost	[0,∞)	%

Table 15: CTV cost inputs

Input Name	Type	Value Range	Unit
Daily charter rate	Charter cost	[0,∞)	$£/vessel$
Annual increase	Charter cost	[0,∞)	%
Annual crew cost	Staff cost	[0,∞)	$£/pp$
Annual increase	Staff cost	[0,∞)	%
Annual O&M technician cost	Staff cost	[0,∞)	$£/pp$
Annual increase	Staff cost	[0,∞)	%
Fuel cost	Fuel cost	[0,∞)	$£/m^3$
Annual increase	Fuel cost	[0,∞)	%
Annual fixed cost	Fixed cost	[0,∞)	£
Annual increase	Fixed cost	[0,∞)	%

Table 16: Turbine component cost inputs

Input Name	Type	Value Range	Unit
Component repair cost	OEM cost	[0,∞)	£
Annual increase	OEM cost	[0,∞)	%

4.4 Analysis/Calculation sections

4.4.1 Climate generation block

Generally historical climate datasets are not sufficient to cover the entire lifecycle of offshore wind farms. Although the data may cover the past 20-25 years, it is rare that the climate data will present exactly the same track in the following years. On the other hand, it is important to generate datasets that preserve characteristics of the original dataset. The generation of different climate datasets minimises the uncertainty of the results. If a single dataset is employed in the simulations, the risk of experiencing worse climate conditions may be ignored. Similarly, experiencing better climate conditions in the future may create risk on the power production values. Therefore, wind speed, wave height, and wave period historical time series are modelled; and the developed climate model is employed to generate data for wind speed, wave height, and wave period time series at the beginning of each simulation. The sequence of the climate generation logic is first defining a model which represents the original time series data and then, generating new time series data by employing the defined model and new inputs. Therefore, each simulation is run under different climate conditions. In order to control and assess the relationship between the generated datasets and the original dataset, annual distributions, maximum weather window periods, correlations between individual datasets (wind speed, wave height and wave period), and autocorrelation functions are compared and illustrated. Due to the fact that it is intended to perform medium to long term analysis and calculations, representing generic characteristics of the original dataset is significantly important.

In this context, Autoregressive Integrated Moving Average (ARIMA) models, which are originally proposed by Box and Jenkins, and Artificial Neural Networks (ANNs) are the most common approaches to solve time series modelling problems, especially due to their fast and robust implementation (Sfetsos, 2002). ANNs are flexible and able to explore trends in the data and develop any linear and non-linear system models to perform reliable predictions (Haykin, 1999, Aires *et al.*, 2004, Samarasinghe, 2007). Moreover, ANNs outperforms ARIMA models (Mohandes *et al.*, 1998, Prybutok *et al.*, 2000). Valipour *et al.* (2013) proved that ANNs have better ability to model longer horizons. Due to these advantages, ANN is selected for the climate modelling.

4.4.1.1 *Data generation*

Introductory information about the climate model algorithm and ANNs is provided in Appendix B. After modelling the climate by artificial neural networks, the major stage is climate data generation through the identified network structure. It is important to highlight that the outputs of the network is dependent on the network inputs; since the structure of the network is already defined and does not change in the data generation stage. It is intended to generate different climate datasets for each simulation, which include wind speed, wave height, wave period values, ensuring the general characteristics (e.g. mean, maximum weather window, annual distribution) of the original dataset are preserved. Therefore, different datasets has to be employed as the inputs of the network structure. The variations on the data are provided through a random selection process. The original dataset, which includes wind speed, wave height, and wave period observations are divided into multiple yearly datasets, number of which is defined by the duration of the original dataset, $L_o(years)$. All the divided datasets comprise wind speed, wave height, and wave period observations gathered within a period of 1 year. In order to preserve the correlation between wind speed and wave height observations, these datasets are not disjointed from each other.

Thereafter, a discrete uniform distribution, which defines equal weights on the integers from 1 to $L_o(years)$, is utilised for random sampling process. In this respect, each integer symbolises one of the pre-divided datasets; thus the selection of an integer indicates the selection of a pre-divided dataset which is represented by that integer. The sampling procedure involves choosing random samples with replacement which means that every sample is returned to the dataset after sampling. So a particular integer from the original dataset could appear multiple occasions. Random sampling continues until the number of randomly selected integers becomes equal to the defined simulation period, $L_{sim}(years)$. The order of the selected integers defines the form of the generated dataset which is utilised in the simulation. This procedure is repeated for each simulation to sustain the uncertainty and unpredictability of the climate parameters.

4.4.2 Vessel operability analysis and transit time calculation block

4.4.2.1 CTV operability and transit time

Despite the fact that previous models and methodologies did not consider the effect of transit time on the O&M activities, especially for the CTV operations, it is believed that environmental conditions cause significant delays for the journeys. In this context, transit time calculations are performed for each CTV in the O&M fleet in order to calculate 'travel time', 'idle time', and 'productive time' for each day of the simulations through considering each time step has different climate characteristics (different wind speed, wave height, and wave period). 'Travel time' is the theoretical time that is spent on the vessel journey (incoming and outgoing), 'productive time' is the theoretical time that is spent on the offshore wind turbine for the actual, value added O&M activity, and 'idle time' is the theoretical time when CTVs are moored in the port due to weather restrictions. One additional point is that the environmental conditions may allow O&M activities at different limited time periods in the same day, for instance 2 hours in the morning, 5 hours in the afternoon. In this case, the model considers the maximum weather window in that shift and allocates the CTVs in this period. It is considered that between departure and arrival of the CTVs, the environmental conditions will be suitable enough for sailing without any interruption.

The transit time is calculated by the division of total distance between the loading port and the offshore wind farm to the vessel speed V. The total distance between the loading port and the offshore wind farm is a constant input for the transit time calculations. However, the vessel speed is not a constant value, even though previous studies assumed it as a constant value. The variations on the vessel speed due to environmental effects create fluctuations in the transit time calculations. Therefore, it is important to calculate the speed of the vessel accurately for each time step.

$$Transit\ Time = Total\ Distance/V \qquad \text{Equation 6}$$

The transit time calculations are performed through calculating the individual distances that are logged by the vessel in each time step, as shown in Figure 29. The time steps in this figure denote the time steps for each 'minute' of the simulation period. Although one minute interval requires large number of calculation steps, it is important to calculate the transit time accurately. For instance, if hourly climate data is modelled in the simulations and if the distance can be travelled in half an hour, it would not be possible to calculate the ‘half an hour’ travel distance by only performing transit time calculations on hourly basis. In this context, the climate observation are replicated to represent each minute of the simulations. It is assumed that climate parameters are identical within the interval period. A CTV starts its journey from the port at the beginning of a working shift. The distance that can be logged during a time step is dependent on the vessel resistance and the vessel specification. It is important to highlight that the human performance/response is not in the scope of the transit time calculations; therefore the focus of the transit time calculations is only vessel performance. When the summation of individual distances becomes equal to the total distance between the loading port and the offshore wind farm, it is assumed that the vessel arrives at the offshore wind farm. Thus,

$$Distance_i = Time\ step\ interval / V_i \quad \text{Equation 7}$$

$$Total\ Distance = \sum_{i}^{n} Distance_i \quad \text{Equation 8}$$

where V_i is the vessel speed at time-step i, $distance_i$ is the distance that is logged at time-step i, n is the number of time steps. In order to verify the vessel speed V_i in each time-step; resistance and power calculations are performed for each individual CTVs in the O&M fleet under different environmental conditions.

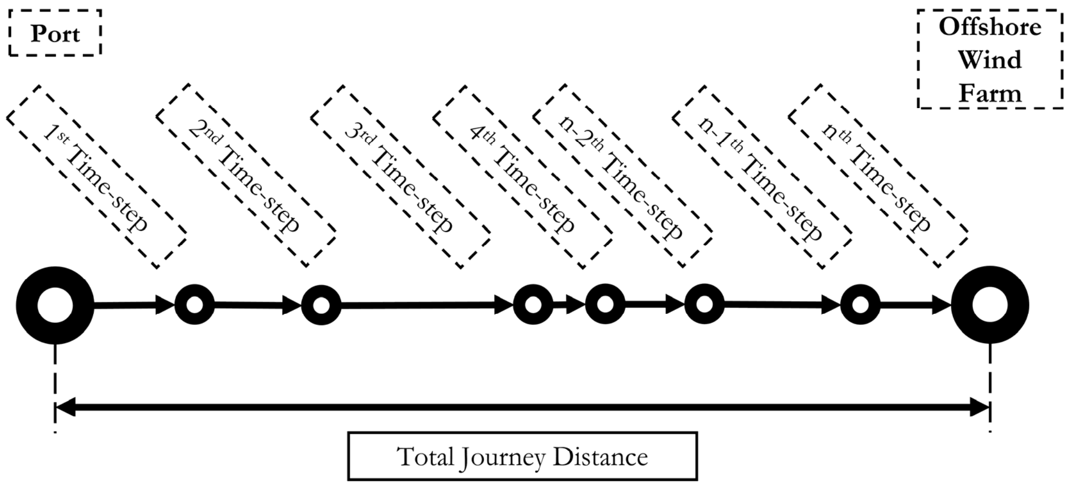

Figure 29: Calculation of transit time

The steps below are followed in the transit time modelling, and repeated for each CTV;

- Calculation of total efficiency
- Calculation of calm water resistance
- Calculation of added resistance and total resistance

- Calculation of speed loss and achievable speed for each time speed in waves
- Calculation of transit time and total fuel consumption through utilising achievable speed, time step interval and the total distance between local port and offshore wind farm

- Calculation of total efficiency

The propeller of a ship can be considered as an energy-converter, which transforms the torque into thrust with the rotational speed of the propeller. The torque required by the propeller must be in equilibrium with the torque delivered by the engine; and the thrust delivered by the propeller also must be in equilibrium with the total resistance of the ship in the self-propelled condition.

The total efficiency of CTV η_T can be written as follows;

$$\eta_T = \frac{P_E}{P_B} = \frac{P_E}{P_T} * \frac{P_T}{P_D} * \frac{P_D}{P_B} = \eta_H * \eta_B * \eta_S = \eta_H * \eta_O * \eta_R * \eta_S \qquad \text{Equation 9}$$

- Effective Power, P_E, is the necessary power to move the ship through the water.
- P_T is the thrust power delivered by the propeller.
- The power delivered to the propeller, P_D, in order to move the ship at speed V is influenced by the flow conditions around the propeller and the propeller efficiency itself.
- The effective brake power, P_B, is power output of the drive shaft of an engine without the power loss caused by gears, transmission, friction etc.
- The hull efficiency, η_H, is defined as the ratio between the effective power and the thrust power which the propeller delivers to the water. η_H can be defined as follows:

$$\eta_H = \frac{(1-t)}{(1 - w_T)} \qquad \text{Equation 10}$$

where t is the thrust deduction factor, and w_T is the wake fraction. In addition, Helm (1980) provided an alternative formulation for η_H of small ships:

$$\eta_H = 0.895 - \frac{0.0065\,L}{\nabla^{1/3}} - 0.005\frac{B}{T} - 0.033C_p + 0.2C_M + 0.01lcb \qquad \text{Equation 11}$$

- Open water propeller efficiency, η_O, is related to working in open water, such as the propeller works in a homogeneous wake field with no hull in front of it.

$$\eta_O = \frac{Power\ output}{Power\ input} \qquad \text{Equation 12}$$

  There are open water propeller efficiency charts available for specific propeller types; however, in some cases the offshore wind farm developers may not able to access the propeller information before chartering the fleet. Therefore, the open water propeller efficiency can be assumed between 0.35 and 0.75, which the high value are generally valid for propellers with a high speed (MAN Diesel & Turbo, 2011).

- The actual velocity of the water flowing to the propeller behind the hull is neither constant nor at right angles to the propeller's disk area, but has a kind of rotational flow. The efficiency of a propeller in the wake behind the ship is not the same as the efficiency of the same propeller under the conditions of the open water test; due to the fact that the level of turbulence in the flow is low in an open water test in a towing tank, whereas it is very high in the wake behind a hull and the flow behind a hull is non-uniform so that flow conditions at each radius are different from the open water test. Therefore, compared with when the propeller is working in open water, the propeller's efficiency is affected by the η_R factor, called the propeller's relative rotative efficiency. Helm (1980) provides an equation for the calculation of propeller's relative rotative efficiency of small ships;

$$\eta_R = 0.826 - 0.01\frac{L}{\nabla^{1/3}} + 0.02\frac{B}{T}0.1C_M \qquad \text{Equation 13}$$

- Propeller efficiency, η_B, is the ratio between the thrust power P_T, which the propeller delivers to the water while working behind the ship, and the power, P_D, which is delivered to the propeller by the shaft of the vessel. Propulsive efficiency, η_D, is equal to the ratio between the effective power, P_E, and the necessary power delivered to the propeller, P_D.

- The shaft efficiency, η_S, depends on the alignment and lubrication of the shaft bearings, and on the reduction gear, if installed. The transmission loss between the engine and the propeller is 2% for direct drive engines and 5% if gearbox is installed (Molland *et al.*, 2011). The total efficiency, η_T, which is equal to the ratio between the effective power, P_E, and the necessary brake power, P_B, delivered by the main engine of the ship.

- Calculation of calm water resistance

The main engine power, P_B, can be gathered from main engine manufacturer leaflets for the CTVs in the vessel pool. η_T is calculated in the previous section, therefore when the P_B is defined, the total calm resistance, $R_{T_{Calm}}$ of a CTV is

$$P_E = P_B/\eta_T \qquad \text{Equation 14}$$

$$R_{T_{Calm}} = P_E/V \qquad \text{Equation 15}$$

However, these equations are valid assuming the ship is sailing in calm water, which is not always the case in the operational environment. When sailing in rough seas with heavy wave resistance, the propeller can be run up to 7-8% heavier than in calm weather. Besides the sea margin, engine margin 10-15% is frequently added as an operational margin for the engine (MAN Diesel & Turbo, 2011). The corresponding term is called the continuous service power and refers to the fact that the power for continuous service is 10-15% lower than the maximum power of the engine. Therefore, installed power on the CTV will be scaled down as the ratio of power for continuous service to the maximum power of the engine in order to define the break power, P_B.

- Calculation of added resistance and total resistance

In the added resistance calculations, the formulations developed by Jinkine and Ferdinande (1973), are utilised. These empirical equations can be used for predicting the added resistance of ships in head seas. The experimental curves of the non-dimensional added resistant coefficient, σ_{AW}, plotted against wave frequency, ω, could be approximated by the following equation;

$$\frac{\sigma_{AW_i}}{r_{max}} = \left(\frac{\omega_i}{\omega_{max}}\right)^{b_i} \exp\left\{\frac{b_i}{d_i}\left[1 - \left(\frac{\omega_i}{\omega_{max}}\right)^{d_i}\right]\right\} \qquad \text{Equation 16}$$

where

$$b = \begin{cases} 11 & \omega \leq \omega_{max} \\ -8.5 & \omega > \omega_{max} \end{cases} \qquad \text{Equation 17}$$

$$d = \begin{cases} 14 & \omega \leq \omega_{max} \\ -14 & \omega > \omega_{max} \end{cases}$$ Equation 18

$$\omega_{max}\sqrt{L/g} = 1.17Fn^{-1/7}\left(k_{yy}/L\right)^{-1/3}$$ Equation 19

$$r_{max} = 3600\left(k_{yy}/L\right)^2 Fn^{1.5} exp(-3.5Fn)$$ Equation 20

The dimensional added resistance is related to the non-dimensional added resistance coefficient by

$$R_{AW_i} = \sigma_{AW_i}\left(\rho g \zeta_{A_i}^2 B^2/L\right)$$ Equation 21

and total resistance of the CTV at ith time step can be calculated by;

$$R_{T_i} = R_{AW_i} + R_{T_{Calm}}$$ Equation 22

Headings are given in terms of the relative heading of the waves compared with that of the vessel track (head seas = 180º; following seas = 0º; starboard beam seas = 90º, port beam = 270º etc.). When compared with the ship's stability characteristics in still water, following waves can lead to a considerable reduction of the transverse stability and unacceptable large roll angles can be the observed. Soares and Teixeira (2001) agreed that following seas may lead pure loss of stability, surf riding and parametric excitation. With regard to beam seas, high-speed vessel are expected pure loss of stability which may cause capsizing, due to the fact that roll motions for these vessels have fully developed in beam seas (Umeda *et al.*, 1992). Therefore, it is expected that CTVs will travel in heading seas. In addition to the stability and manoeuvrability issues, current added resistance calculations with beam and following seas are not as accurate as the added resistance calculations with heading seas; therefore in the transit model block, added resistance calculation are performed assuming that CTVs travel in a heading sea.

- Calculation of speed loss

Whilst a CTV is traveling in a wavy sea, skipper can keep the power constant and decrease the speed or keep the speed constant and increase the power. In the transit model block, the power and thrust of the CTVs will be kept constant and speed will change with the influence of waves. This assumption will lead to constant fuel consumption with a single interval. It should not be forgotten that the total fuel consumption of CTVs will vary with the influence of fluctuations on the total travel time.

In order to calculate the speed loss in each time step under the condition of constant power and thrust, the formulation derived by Berlekom *et al.* (1974) and Berlekom (1981) can be utilised.

$$\frac{\Delta V_i}{V_0} = \sqrt{1 + \frac{R_{AW_i}}{R_{T_i}}} - 1 \qquad \text{Equation 23}$$

It would be possible to calculate the speed loss in each time step through the calm water resistance and added resistance values, which are calculated in the previous sections. Thus,

$$V_{a_i} = V_0 - \Delta V_i \qquad \text{Equation 24}$$

where V_{a_i} is the achievable speed by the vessel at ith time step.

It should be highlighted that in the case of weather conditions do not allow or predefined restrictions such as maximum operational wind speed, maximum operational wave height, etc., exceed the associated observation at a time step, the achievable speed will be defined as zero.

- Calculation of transit time

After calculating the achievable speed for each time step, the following task is the calculation of distance which vessel can log in each resolution interval.

$$Distance_i = Time\ Step\ Interval \times V_{a_i} \qquad \text{Equation 25}$$

The fuel consumption values can be gathered from engine manufacturer product manuals. Due to the fact that the power and thrust are constant, the fuel consumption of the vessel on the resolution bases will also be constant. However, due to the change in the vessel speed, there will be variations in the total time spent for the incoming and outgoing journeys which will create fluctuations in the fuel cost calculations.

4.4.2.2 CTV accessibility

The CTV accessibility is the key aspect, which is also considered in the methodology. The CTV accessibility implies the climate conditions that the O&M technicians can have safe access to the turbines. In this respect, the wind speed limit at sea level and wave height parameter are taken into account. In order to perform a safe access, both conditions have to be met. An extra limitation for the CTV accessibility is the daylight period. In accordance with the discussions with the industry experts, it is assumed that CTVs can perform technician transfer after the sun rises; in the same manner CTVs have to pick up the technicians before the sun sets. CTVs can sail before the sun rises or after the sun sets; however, the O&M technician transfer can be performed when there is enough daylight at the site. The CTV accessibility is an important measure, because even though CTVs can sail in rough conditions, if the technicians cannot be allocated to the turbines, this is not a valuable travel from O&M point of view. Due to safety reasons, it is envisaged that the accessibility limits have to be met during the entire O&M activity. Therefore, in an emergency situation, the O&M technicians can be transferred back to CTVs.

4.4.2.3 Jack-up operability and transit time

In the current operational environment, a jack-up is generally required two times in the operational span of a turbine. Furthermore, the transit time is negligible when compared to mobilisation time and the length of actual O&M activity. Therefore, the transit time of the jack-up vessel is assumed to be included in the mobilisation time.

In this context, the major repair/replacement restrictions comprise surviving, jacking and operating constraints. In extreme storm conditions, the jack-up vessel cannot sail, operate or perform any maintenance activity due to high risk of sinking and capsizing. In this case, the vessel has to be kept in the specified port. It is assumed that the major repairs cannot be suspended after repair activity is started; therefore the jack-up vessel can only start the O&M activity, if there is no expected storm during repair period. Storm conditions are defined by limiting significant wave height (H_S) and surviving wind speed at sea level.

In order to start jacking-up operation, the minimum weather window should be longer than the time required for jacking-up. In this case, the minimum weather window is defined by the consecutive time steps in which Hs and wind speed values are lower than the limiting Hs and wind speed for jacking operation. If the minimum weather window is shorter than the jacking-up period, the vessel waits at the site until the conditions are met. When the minimum weather window is sufficient enough, the vessel jacks-up.

Due to the fact that the major O&M activities require heavy equipment lifting, wind speed at hub level is an extra limitation for the jack-up O&M operations. As for the jacking operation, the minimum weather window should be longer than the time required to perform the repair or the replacement. If the weather window is shorter than the repair period, the vessel waits as jacked-up until the conditions are met.

4.4.3 Failure simulation block

4.4.3.1 Pseudorandom numbers generation

A time domain Monte-Carlo approach is adopted to simulate the failures, which relies on random number generation to ensure that all possibilities are covered in an unbiased manner. Such an approach requires deterministic and stochastic events. While the former is governed by the inputs and the assumptions; turbine failures and weather conditions comprise the stochastic elements of the simulation. During a simulation each operational turbine is given the chance to fail at each time step. At this point, the model cycles through the simulation schedule in a randomised order. For each time step, pseudorandom numbers between 0 and 1 are generated from a uniform distribution. Figure 30 is sample representation of generated 10^5 pseudorandom numbers.

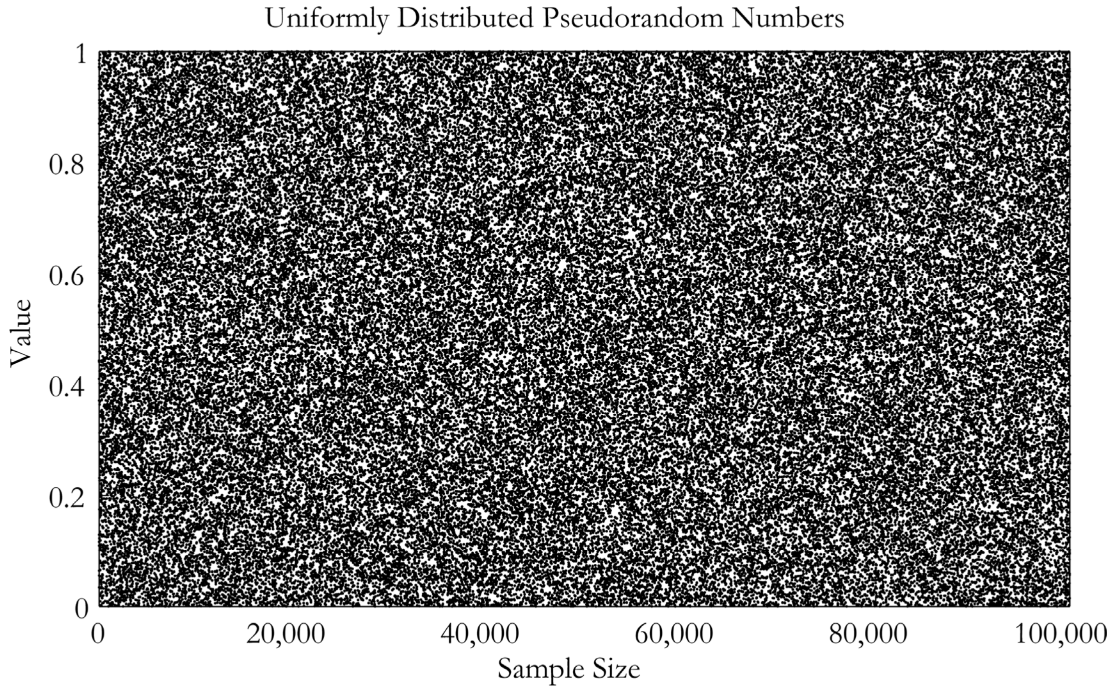

Figure 30: Pseudorandom numbers

4.4.3.2 Assigning components to turbines

In some cases, especially if an operating wind farm is simulated, some of the components may have been repaired or replaced before the simulations are run; therefore, the age of the components may vary within a single turbine and also throughout offshore wind farm. If the turbine component failure rates are constant, the failure rates are not dependent on the age of the component; however, if the turbine component failure rates are time dependent, the age of the component or the last time that that particular component is repaired may change the total turbine failure rate significantly. Figure 31 is a particular example, which demonstrates the influence of the component ages on the turbine system failure rate. In this figure, sample bathtub curve failure distributions are employed. The thick black coloured lines in both figures shows the turbine system failure rate, and the other colours show the turbine component failure rates. In the top graph, at the beginning year 1, the turbine system failure rate is just below 10 and decreases within time; since the age of the components are defined as '0', which defines the component failures rates in wear-in period. On the contrary, the age of the components are defined as '15' in the bottom graph. Therefore, the component failure rates are tend to increase due to wear-out effect.

In order to demonstrate the influence of component ages in the methodology, the name of the turbine components are listed and grouped according to their ages. At this stage, the name of the turbine components, the total number of turbine components in the offshore wind farm, and the age distribution of the turbine components are identified. At the beginning of each simulation, the age values are associated with the turbine components randomly. Thereafter, the components, with defined ages, are distributed to individual turbines randomly. It is important to highlight that each turbine has the same component configuration, therefore once a particular component is distributed to a turbine, it cannot be selected again. Due to the fact that the turbine components are distributed randomly, the age of the components in each turbine will vary.

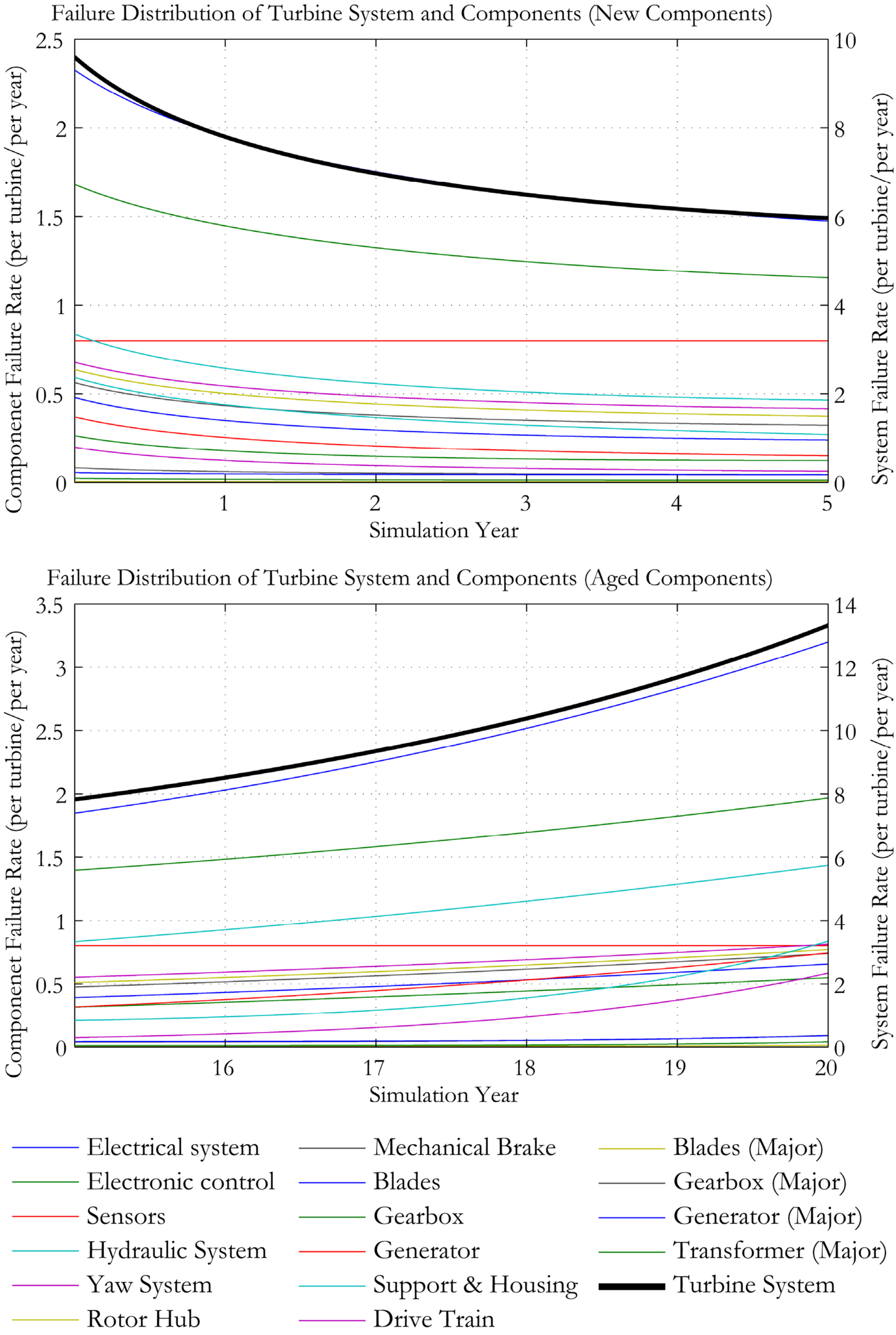

Figure 31: Failure rate distributions for new and aged components

4.4.3.3 Calculation of turbine failure rate

The first step of the failure identification is the calculation of turbine system failure rate based on the component failure rates. In this context, the performance of each component i can be represented by a binary indicator variable x_i, where,

$$x_i = \begin{cases} 1, & \text{if component is functioning,} \\ 0, & \text{if component is failed} \end{cases} \quad \text{Equation 26}$$

for $i = 1, 2, \dots, n$, where *n* is the number of components in the system. Similarly, a binary variable $\emptyset$ denotes the state of the turbine system.

$$\emptyset_\mathrm{i} = \begin{cases} 1, & \text{if turbine system is functioning,} \\ 0, & \text{if turbine system is failed} \end{cases} \quad \text{Equation 27}$$

The reliability R, failure density function f and time dependent failure rate λ of a system at time t are

$$R(t) = e^{-\int_0^t \lambda(t)\,dt} \quad \text{Equation 28}$$

$$f(t) = -dR(t)/dt \quad \text{Equation 29}$$

$$\lambda(t) = -\frac{1}{R(t)}\frac{dR(t)}{dt} \quad \text{Equation 30}$$

In a series system, the system can function if and only if all components are in the functioning state. Otherwise, the entire system fails. The series system does not imply physical series connections of electrical or mechanical components. It refers to how such product failure depends on component failure. The reliability of a series system R_s at time t is

$$R_s(t) = \prod_{i=1}^{n} e^{-\lambda_i t} \quad \text{Equation 31}$$

In a parallel system, the system fails if all components fail or the system performs satisfactorily if at least one of the n components performs satisfactorily, which is also called redundancy. The reliability of a parallel system R_p at time t is

$$R_p(t) = 1 - \prod_{i=1}^{m}(1 - R_i) \quad \text{Equation 32}$$

The turbine system can be either series or parallel or the combination of those systems. Depending on how the system is structured, the turbine failure rate is calculated from individual component failure rates.

4.4.3.4 Turbine failure identification

The generated pseudorandom numbers and the turbine system failure rates are employed in the turbine failure identification stage. In this context, the number of generated pseudorandom numbers at each time step is equal to the number of turbines in the offshore wind farm (i.e. 100 numbers for 100 turbines or 300 numbers for 300 turbines); therefore, each pseudorandom number is associated with a single turbine. If the generated pseudorandom number is lower than the associated turbine failure probability in a particular time step, it indicates that the turbine fails in that time step, otherwise continues functioning. Through explained method, the turbine failure time steps and the failed turbines in those particular time steps can be identified. If the simulation period is relatively short and the failure probability of the turbines is significantly low, all the generated pseudorandom numbers associated with specific turbines may always be higher than the failure probability of the turbines within the simulation period; in this case, it is envisaged that those specific turbines do not fail within simulation period.

4.4.3.5 Component failure identification

In the previous section, the failed turbines and the failure time-steps are identified. Thereafter, it is important to identify the individual components that cause failure and the type of failure, whether it is a minor or major failure. In this respect, the failure rate information provided to run the failure simulations has a crucial importance. Three different cases are modelled within the methodology;

- If individual failure rates are defined for each turbine component and failure type. For instance if the turbine generator has a failure rate for minor failures and has another failure rate for major failures.
- If individual failure rates are defined for each turbine component but the failure type is alternatively defined by a probability. For instance if the turbine generator has a generic failure rate and when a generator failure occurs it is expected that 20% probability a major failure occurs and 80% probability a minor failure occurs (Pareto Analysis).

- If minor and major failures are defined individually for each component (combination of the first two cases). For instance, if the turbine generator has a failure rate for minor failures and has another failure rate for major failures; on the other hand, if the turbine gearbox has a generic failure rate and when a gearbox failure occurs it is expected that 20% probability a major failure occurs and 80% probability a minor failure occurs.

In all cases, imaginary weights are defined and distributed to each turbine component. The summation of the imaginary weights is always equal to 1, but the value of each weight is directly proportional to the failure rate of each turbine component. Therefore, the turbine components, which have higher failure rates, are presented by higher weights; on the contrary, the turbine components, which have relatively lower failure rates, are presented by lower weights. After defining the weights for each turbine component, a random sampling process (considering the defined weights) is performed in order to identify the turbine component that caused failure. Due to the nature of random sampling process, the turbine components, which have higher weights in the distribution, are more likely to fail; on the contrary the turbine components, which have lower weights in the distribution, are less likely to fail. Furthermore, the sampling procedure involves choosing random samples with replacement, which means that every sample is returned to the dataset after sampling. So every component or every failure type have a particular probability to occur again in the following time steps within the simulation.

If the turbine component failures are defined through the first case (failure rate for each turbine component and failure type), the failed turbine components and failure types can be identified in a single step. However, if the turbine component failure rates are defined through the second case or the third case (generic failure rate and defined failure probabilities for minor and major failures), an additional process is followed in order to identify the failure type; since, only failed turbine components can be defined through these cases. In this respect, weight are defined for each failure type, which the summation of weights are equal to 1 and the values of weights are directly proportional to the probability of failure types on the overall failure probability. After defining the weights for each failure type, a random sampling process (considering the defined weights) is performed in order to identify the failure type.

4.4.3.6 Failure rate progress

At the beginning of a simulation, time steps of the first failures and the components that are failed for each turbine are identified through the explained approach. After this stage, the analysis continues separately for each turbine. A vessel is allocated for the turbine which is failed first and the repair is performed. The details about the repair strategy and the vessel allocation are given in the following sections. When the failure is repaired and the time step, at which the turbine starts functioning again is identified, the failure rate of the failed component is reset to the beginning level, as the repaired component is assumed 'as good as new' condition. Due to the fact that other components remain untouched within the repair period, the failure distributions of those components are shifted forward to the time step which the turbine starts to function. Thus, the failure distributions of these components continue from the level at which the failure has occurred; however the distribution of the failed component is reset which requires an update on the system failure distribution regardless of whether the system is parallel or series.

In this respect, the failure distributions of the components and the system are updated, and a new Monte-Carlo simulation is run from the time step, at which the turbine starts to function, until the end of the simulation period through using the updated failure distribution of the system. As a result of the new Monte-Carlo simulation, the subsequent failure of the turbine is identified. If there is no subsequent failure for that specific turbine or the time is not enough to repair the failure within the simulation period, the following failure type of that specific turbine is set to infinity (INF).

If there are multiple turbine failures on the same day of the simulations, those failures are simulated separately. The simulations continue until all the subsequent failure types for all turbines are set to INF which is generally at the very end of the simulation period. The definition of all the following failure types to INF indicates that either any new failure will not occur after that specific time step or the current failures cannot be repaired which also means that a failure cannot occur because the situation of the turbine will not change from failed state to functioning state.

4.4.4 Repair simulation block

The main concept of the repair strategy is, examining the reliability at the component level, whilst structuring the O&M activities at the wind farm level. Therefore, the characteristics of individual wind turbine components play a key role in the reliability analysis; however final O&M decisions are made by considering the offshore wind farm as a single unit.

In this context, when a failure occurs, the turbine is shut down and the subsequent activities continue depending on the type of failure and type of vessel required to repair that failure. The vessel type selection is governed by the failure mode. As explained in the component failure identification stage, the major failures are linked to jack-up vessel and the minor failures are linked to CTVs. Therefore, when the failure is identified, whether is a major failure or a minor failure; required vessel is allocated automatically by the simulation logic.

4.4.4.1 Failures require a jack-up vessel

Figure 33 is the graphical presentation of how the repairs are performed if a jack-up vessel is required to repair the failure. If the failure requires a jack vessel, the first step is identifying whether there is an available jack-up vessel at the offshore wind farm at the failure time-step. This information is also related to the chartering strategy of the jack-up vessel. If the operator decides to have a time charter contract, the vessel either stays at the specified port or performs maintenance tasks at the site during agreed charter period. Therefore, the vessel is assumed to be always available during charter period, excluding the days that the vessel is allocated for a repair task. If the operator decides to have spot charter contract, mobilisation time has to be included in order to allocate the vessel to a repair task. In this case, the vessel stays at the site for a limited period (charter period) and leaves the site either the charter period is completed or all the maintenance tasks are completed. In some circumstances, a new failure may occur during the mobilisation period of the jack-up vessel, which is chartered to perform an existing failure repair. In this case, a new jack-up vessel is not chartered, instead, the remaining mobilisation time is waited and the same jack-up vessel is utilised for the subsequent failure after the repair task of the existing failure is completed.

The methodology is modelled to maximise the wind farm productivity and optimise the total O&M cost; therefore, if there are remaining repair tasks to be performed, the jack-up vessel does not leave the site regardless of the remaining charter period and completes the repair tasks. Under spot charter contract, if the actual departure date of the jack-up vessel is later than the end date of the charter period, demurrage cost, which is the money payable to the vessel owner for delays beyond the agreed charter period, is added to the total charter cost and to the total O&M cost. If the remaining charter period is shorter than the required repair time, demurrage is paid subject to the extension on the charter period. Demurrage is assumed to be a function of vessel day rate.

When the jack-up vessel arrives in the offshore wind farm or if there is already a jack-up vessel at the site, the second step is identifying whether the vessel is already allocated to a repair or the vessel is available at the failure time step. If the vessel is already allocated to another repair task, the repair of the subsequent failures can be performed after the current task is completed. If there are multiple failures that the jack-up vessel has to perform, a supply period for fuel, provisions, repair parts, etc. have to be included between consecutive jack-up repair tasks.

It is expected that the technicians on the jack-up vessel work on 3-shift cycle; therefore the repair activities continue for 24 hours/day. The lights on the jack-up vessel (both on-board and on lifting cranes) provide a safe working condition even during night (Figure 32). After completing repair, the vessels can only start jacking-down if the weather window is suitable enough to complete the jacking-down. During mobilisation, jacking-up, actual repair, jacking-down periods, the turbine remains inactive; the turbine starts functioning again 1 time-step after the repair/replacement is completed. A time-step denotes the period of the climate observations (preferably 1-hour or lower).

When a repair task is completed, if there are remaining failures that have to be repaired, the jack-up vessel continues to stay at the site and perform the repair tasks, otherwise the vessel either sails back to port if there is remaining charter period in the spot charter contract or leaves the site. If time charter contract is signed, the jack-up vessel always sails back to port after all the repair tasks are completed.

Figure 32: Jack-up vessel operations during night(Ship-technology, 2015)

4.4.4.2 Failures require a CTV

If the CTV fleet comprises of only a single CTV, all the repairs, which specifically require a CTV to transfer the O&M technicians to the site, can only be performed by that specific CTV. In this case, there is no other option or alternative to that specific CTV in order to transfer the O&M technicians. On the other hand, if the CTV fleet comprises of multiple CTVs, one of the CTVs has to be selected/defined among the CTV fleet and allocated to that specific failure/turbine. As explained in the previous section, the logic behind the methodology is maximising the power production, and optimising the total O&M cost. Therefore, the first step is to identify the CTV, which has enough technicians on-board to perform the repair and enough productive time to complete the repair in a single shift.

- Single shift repairs

Depending on the environmental conditions on the repair day and the operational capabilities of the CTVs in the vessel pool, more than one CTV can be available for the corrective maintenance task (Figure 34). In this case, the CTV, which is already in the offshore wind farm, is allocated to the repair; thus, the vessel utilisation is maximised and downtime is minimised. However, none of the CTVs will be allocated at the beginning of a shift; therefore an additional priority item has to be defined. In this case, the CTV, which provides the longest working period in the repair day, is allocated to the repair. If there are more than one CTV at the site, the CTV, which visited more turbines than the other CTVs in the fleet, is allocated to the repair; thus, again the vessel utilisation is maximised. The first two priority items leads a single CTV to perform as many visits as possible. For instance, if there are three failures to be repaired in a single shift, the approach is allocating (if possible) a single CTV for all the tasks, instead of allocating a CTV for each task.

If there are more than one CTV that performed same number of visits in the repair day, the CTV, which has less number of technicians on-board, is allocated to the repair; so, the CTVs with higher number of technicians on-board remain available for more demanding repair tasks. If there are more than one CTV that fit into this category, the CTV which has lower fuel consumption rate is allocated to the repair; thus, the total CTV fuel cost is minimised. If there are still more than one CTV that fit into this category, the CTV is selected randomly.

- Multiple shift repairs

If the repair task cannot be completed even by the maximum number of technicians in a single shift, the maximum number of technicians will still be allocated to the repair task in the following repair days until the repair task is completed. The works, which are performed in every repair day, are logged; thus the remaining repair can be completed in the following accessible days. At the very last repair day of the multiple shift repairs, if the regular number of technicians is sufficient to complete the repairs in that shift, they are allocated to the turbine, otherwise the maximum number of technicians are allocated to the turbine to complete the repair. The CTV and technician allocation logic in Figure 34 is also considered for the multiple shift repairs; however the priority to complete the repair in a single shift is not valid any longer.

4.4.4.3 Lack of resources

If all the O&M technicians are either occupied with repair operations or not on duty, the turbine remains down, and an O&M technician will not be assigned until the regular number of technicians becomes available to work. When O&M technicians become available and are assigned to conduct the repair work, they can only be deployed to the failed turbine if the current weather conditions are within the turbine access limits as defined in the model inputs. If these conditions are not met, the O&M technicians stay at the base/port and are only dispatched to the assigned turbine once the weather conditions improve within the access limits.

4.4.4.4 Corrective repair and preventive maintenance

- Corrective maintenance

The time taken to repair the turbine, once the O&M technicians are in attendance, is determined by repair time value specified for the failure. The model keeps track of the remaining repair time as the work progresses. Once the repair is completed, the turbine is restarted. If during repair, weather conditions worsen to a level beyond the specified turbine access limits; repair operations are suspended and the crew returns to base. In this instance, the turbine concerned remains inoperative. However, the work which is already performed is logged, thus the remaining repair can be completed in the following accessible day.

It is assumed that the offshore wind farm operator always has enough component in stock to perform the repairs; therefore, the component lead time values are modelled as ‘0’.

- Preventive maintenance

Preventive maintenance is implemented by the same O&M technicians within the specified service interval. Repair work takes precedence over scheduled maintenance, which is suspended if the O&M technicians are required for repairs. If there is sufficient time to perform preventive maintenance after the repair work, the O&M technicians stay in the wind turbine and continue with the preventive maintenance until the time they need to leave the turbine in order to be in the port at the end of shift. Like the repair works, preventive maintenance is also logged for each individual turbine.

However, performing preventive maintenance operations only after corrective maintenance may not be enough to complete the preventive maintenance within the specified service interval, such as if the failure rates are significantly low, so technicians rarely visit the turbines, or if the preventive maintenance requirement is significantly high so technicians require separate visits. In this context, the separate preventive maintenance visits are performed when the wind speed values at hub level are at the minimum level, preferably lower than the turbine cut-in speed. Thus, the power production due to preventive maintenance is minimised.

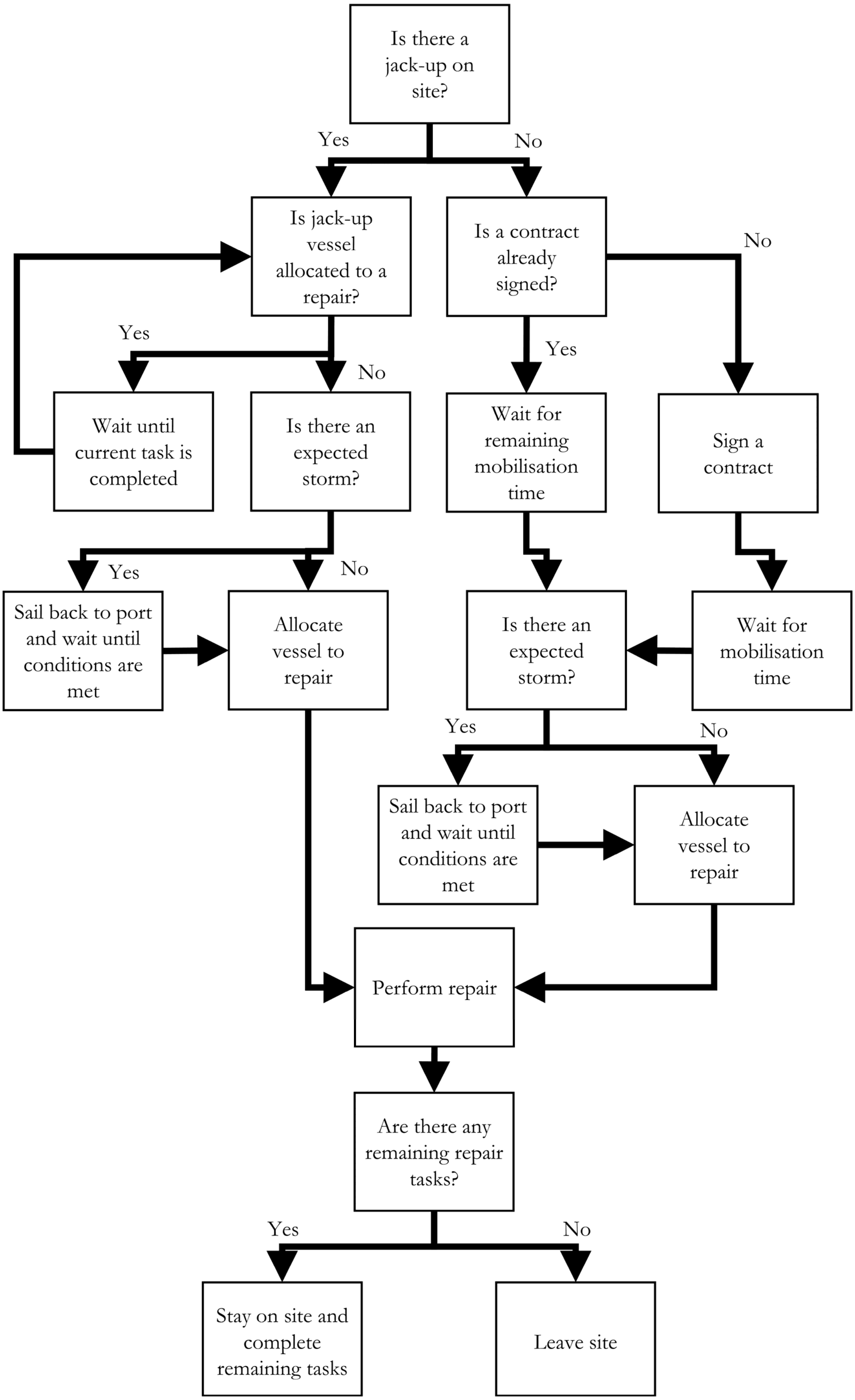

Figure 33: Repair approach for the failures that require jack-up vessel

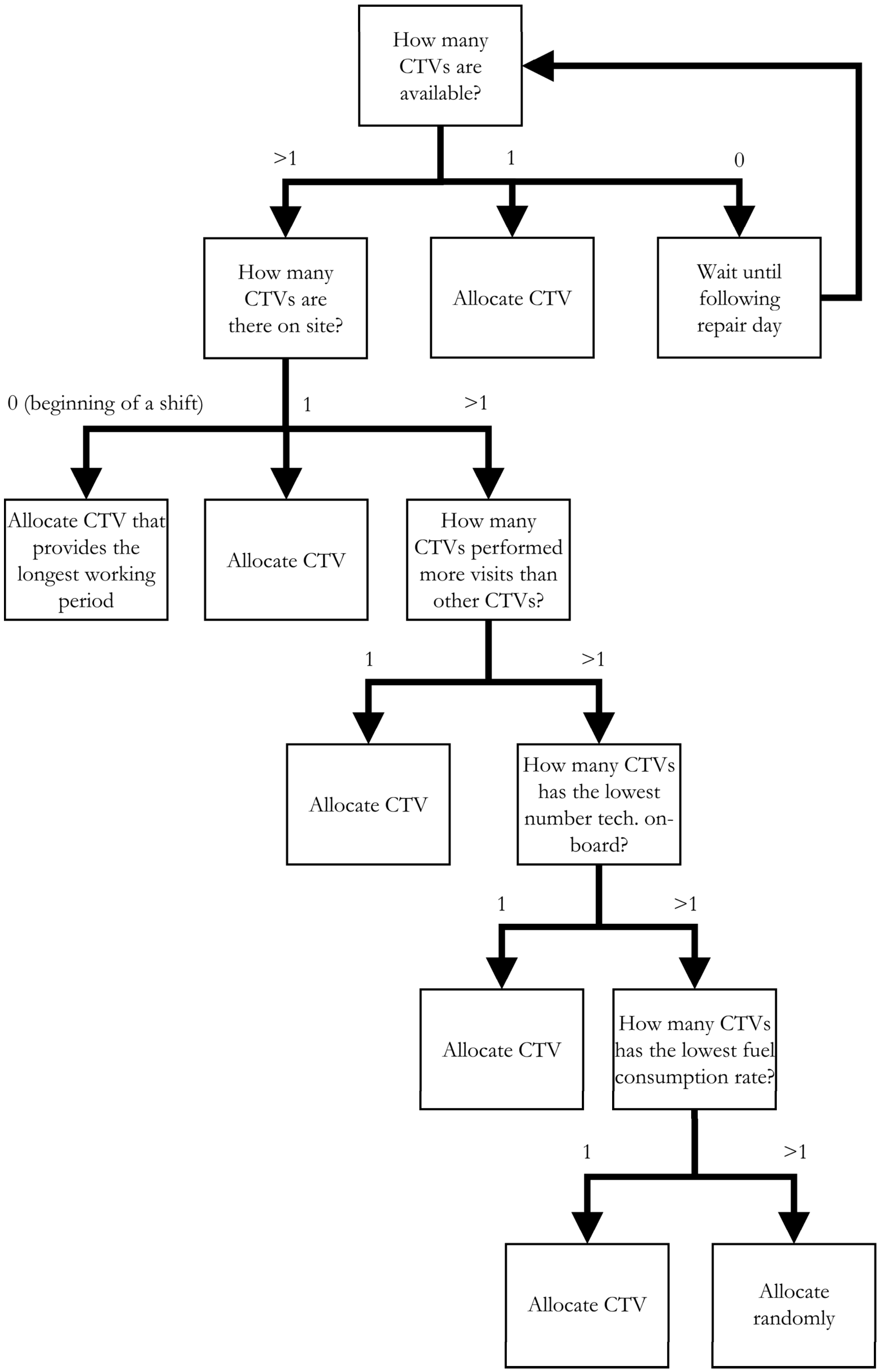

Figure 34: Repair approach for the failures that require CTV

4.4.5 Power calculation block

In the power calculation block, the MTTR and the MTTF values for each turbine and the wind speed values at hub height are synthesised. In this context, the first step is calculating the availability of the turbines within the simulation period. In the repair simulation block, the MTTR and the MTTF values for each individual turbine are stored; therefore, the time-steps, which the wind turbines are either in failed or in functioning condition, can be identified. In order to employ the failed and the functioning time steps in the mathematical equations, the functioning time-steps are represented by 1, and the failed time steps are represented by 0. At the end of the first step, a single column vector, which has the number of rows equal to the number of time steps in the simulation, is created for each offshore wind turbine. These vectors consist of '0's and '1's depending on the condition (failed or functioning) of the turbines.

The second stage is calculation of the power production of each individual offshore wind turbine. In the input sections, the power production values of the wind turbines are provided; however, the power production values are generally provided in a table format, in which a single power production value is associated with a single wind speed value. If the interval of the wind speed values are large (i.e. 1 m/s), the power production values corresponding intermediate wind speed values have to be calculated. In this context, linear, piecewise cubic, and cubic spline interpolation methods are tested, as shown in Figure 35. The piecewise cubic interpolation technique provides better approximation than other techniques in the case that the wind speed interval in the power production table is 1 m/s or more.

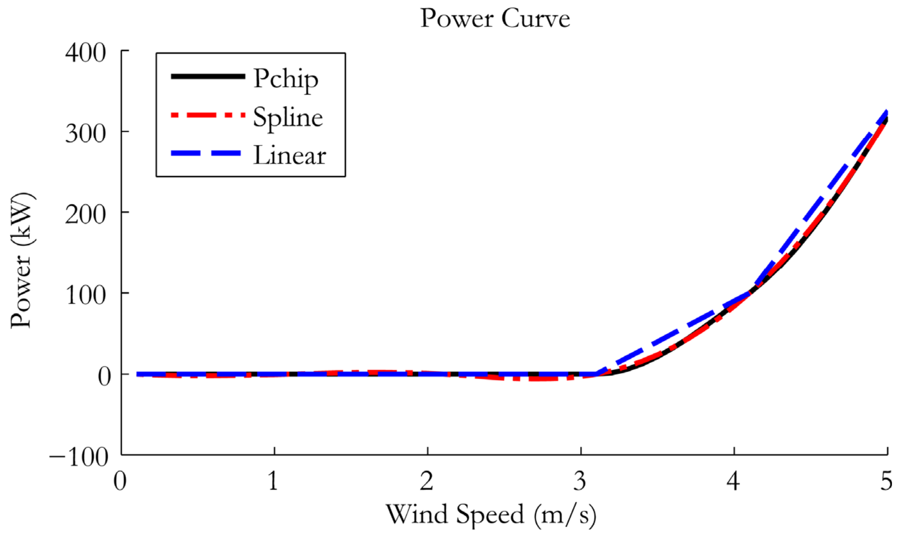

Figure 35: Comparison of interpolation techniques

4.4.5.1 *Piecewise cubic interpolation*

In the piecewise cubic interpolation method, the polynomial is partitioned into N intervals having N+1 nodes and N-1 internal nodes. A different cubic polynomial is created for each subinterval of the polynomial, and the parameters are adjusted in a way that the final point of a cubic polynomial of a subinterval is equal to the start point of the subsequent cubic polynomial of the subsequent subinterval. Therefore, the continuity of the overall polynomial is guaranteed. Figure 36 is an example illustration for the piecewise cubic interpolation method. In this particular example, the polynomial is divided into four different subintervals with having five nodes and three internal nodes. The parameters of each subinterval polynomial are adjusted to provide minimum error for the polynomial values in node points.

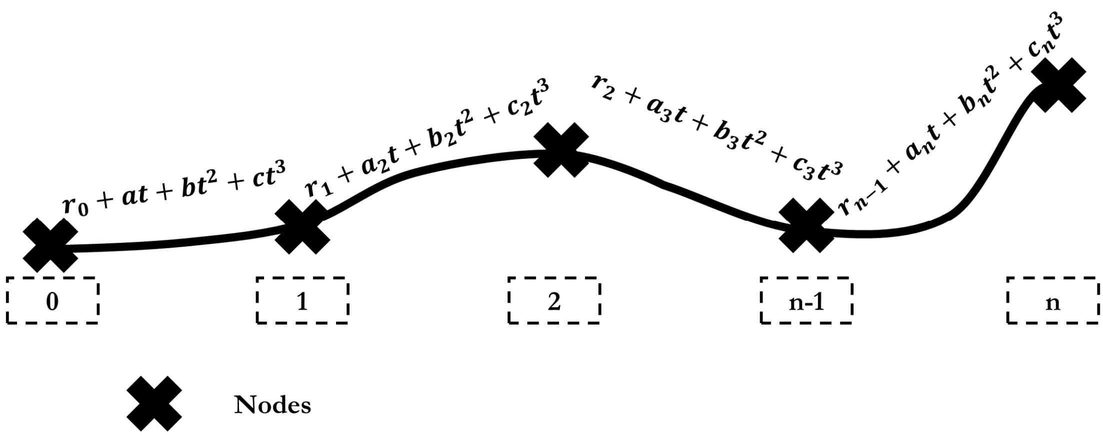

Figure 36: Piecewise cubic interpolation

4.4.5.2 *Calculation of power produced*

In the first stage, a column vector is created for representing the condition (failed or functioning) of each turbine in the offshore wind farm within the simulation period. In the stage, the power production values are interpolated to calculate the theoretical power production of the individual wind turbines. Similar to the turbine condition vector, a column vector is created, which represents the theoretical power production values of each individual wind turbine within simulation period. Figure 37 illustrates how the power production of a turbine is calculated. In the figure, P denotes the interpolated power production values and i denotes the number of time steps in the simulations. The element multiplication of the condition vector and the power vector provides the actual power production values associated with each time step during simulations, and the total power production of the turbine can be calculated by the summation of P values. In order to calculate the power production of the entire offshore wind farm, the calculation steps have to be repeated for each individual turbine in the offshore wind farm, considering the condition vectors are unique for each turbine.

$$\underbrace{\begin{bmatrix} 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ . \\ . \\ . \\ 0 \\ 0 \\ 0 \\ 1 \\ 1 \end{bmatrix}}_{\text{Condition Vector}} x \underbrace{\begin{bmatrix} P_1 \\ P_2 \\ P_3 \\ P_4 \\ P_5 \\ . \\ . \\ . \\ P_{i-4} \\ P_{i-3} \\ P_{i-2} \\ P_{i-1} \\ P_i \end{bmatrix}}_{\text{Power Vector}} = \begin{bmatrix} P_1 \\ P_2 \\ P_3 \\ P_4 \\ P_5 \\ . \\ . \\ . \\ 0 \\ 0 \\ 0 \\ P_{i-1} \\ P_i \end{bmatrix}$$

Figure 37: Power production calculation

$$P_{OWF} = \sum_{i}^{n} P_i \qquad \text{Equation 33}$$

where P is the actual power produced at time step i, n is the number of time step in the simulation, P_{OWF} is the total power production within the entire offshore wind farm.

4.4.5.3 *Calculation of wake effects*

The wake effect is a well-known issue that influences the wind farm performance negatively (Kapsali and Kaldellis, 2012). There are complex models developed by Christiansen and Hasager (2005), de Prada Gil *et al.* (2012), Sebastian and Lackner (2012), and Peña *et al.* (2014), which can model the wake effect considering the wind direction and the offshore wind farm layout. In the methodology, neither wind direction nor offshore wind farm is considered; however the wake effect should be modelled in order to achieve more precise results. In this context, the turbine efficiency equations developed by Barthelmie and Jensen (2010) are employed. Equation 34, Equation 35, and Equation 36 are valid for the wind speed values between 5 – 10 m/s, 10 – 15 m/s, and >15 m/s, respectively.

$$\Delta\ Efficiency\ (\%) = 1.43 * Rotor\ diameter - 20.9 \qquad \text{Equation 34}$$

$$\Delta\ Efficiency\ (\%) = 1.33 * Rotor\ diameter - 19.1 \qquad \text{Equation 35}$$

$$\Delta\ Efficiency\ (\%) = 0.08 * Rotor\ diameter - 1 \qquad \text{Equation 36}$$

The theoretical power production values of all the turbines are updated in accordance with the efficiency values calculated using the equations above. In addition, individual turbine power efficiency values with respect to array average are provided in Barthelmie and Jensen (2010). In the wind farm, some turbines contribute to the power production more than other turbines due to the direction of the wind and the layout of the wind farm. Therefore, some turbines have positive efficiency, some of the turbines have negative efficiency relative to the average wind farm efficiency. In this context, a distribution is identified, which represents the individual wind turbine efficiency values best, and random values are generated from the identified distribution in each time step of the simulations. These random values are also associated with the individual turbines randomly. Since all the power production values are decreased by the average wind farm efficiency before, in this stage individual wind turbine efficiency values are reflected on the power production values. If the individual wind turbine efficiency is positive, this particular turbine has a higher efficiency than the average wind farm efficiency. On the contrary, if the individual wind turbine efficiency value is negative, the efficiency of this particular wind turbine is lower than the average wind farm efficiency. Nevertheless, the summation of negative and positive turbine efficiency values equals to zero; therefore, the wind farm efficiency value is captured.

4.4.6 Cost calculation block

In the cost calculation block, the total O&M cost, which comprises of the major costs below, is calculated by Equation 37.

- The total OEM cost,
- The total charter cost,
- The total mobilisation cost,
- The total fuel cost,
- The total staff cost,
- The total fixed cost,
- The total dry-dock cost,
- The total sub-charter cost.

$$\begin{aligned} Total\ O\&M\ Cost &= Total\ OEM\ Cost + Total\ Charter\ Cost \\ &+ Total\ Mobilisation\ Cost + Total\ Fuel\ Cost \\ &+ Total\ Staff\ Cost + Total\ Fixed\ Cost \\ &+ Total\ Drydock\ Cost + Total\ Subcharter\ Cost \end{aligned}$$ Equation 37

The generic principle for the cost calculations is, all the costs listed above are calculated at the end of each simulation for each scenario. Since, multiple simulations are required to run in order to cover all possible situations such as bad weather year and good weather year, or high number of failures and low number of failures, etc., the costs associated with each scenario are averaged when all the simulations are completed. The following sections explain how the different cost attributes are calculated.

4.4.6.1 Calculation of the total OEM cost

In the failure simulation block, the components that are failed, and the time-steps of these failures are tracked. The cost of each component is also defined in the cost specific attributes section. Due to the annual increment factor, the cost of each component needs to be updated in the later stages of the simulation period. The cost of components that are failed within the first year of the simulations is calculated from the base cost rate. The cost rate of each component is updated for the subsequent year in the simulation and therefore, the cost of component may increase/decrease or remain at the same level. The cost update process continues until the end of simulation. At the end, the total OEM cost is calculated from the summation of annual OEM costs.

$$Annual\ OEM\ cost = \sum_{n}^{m} OEM\ cost_n$$ Equation 38

$$Total\ OEM\ cost = \sum_{i}^{y} Annual\ OEM\ cost_i$$ Equation 39

where y is the length of simulation in terms of years, $Annual\ OEM\ cost_i$ is the annual OEM cost within year i, m is the number of components, and $OEM\ cost_n$ is the OEM cost of component n.

4.4.6.2 Calculation of the total charter cost

The total charter cost consists of two sections; the total CTV charter cost and the total jack-up charter cost. It is envisaged that the charter cost of CTVs are calculated for the entire analysis period, regardless of the value of 'travel time' and 'productive time'. It is important to highlight that the charter cost is paid to the vessel owner continuously, even though the utilisation level of the vessel is low. Similar approach is also followed for the annual cost increase; therefore the base charter cost, which is defined in the cost specific attributes, is considered within the first year of the simulations. In the subsequent years, the charter cost is increased by the 'annual increase' value. The total CTV charter cost can be calculated by the equations below,

$$Annual\ CTV\ charter\ cost = \sum_{n}^{m} CTV_n\ daily\ charter\ cost * 365 \qquad \text{Equation 40}$$

$$Total\ CTV\ charter\ cost = \sum_{i}^{y} Annual\ CTV\ charter\ cost_i \qquad \text{Equation 41}$$

where $CTV_n\ daily\ charter\ cost$ is the daily charter cost of the nth CTV in the fleet, m is the number of CTVs in the fleet, $Annual\ CTV\ charter\ cost_i$ is the annual CTV charter cost within year i, y is the length of simulations in terms of year. It is important to highlight that the CTV fleet may compose of different CTVs; therefore, the daily charter cost of each CTV may differ depending on its operational capabilities.

The total charter cost of jack-up vessel is strongly correlated with the charter type and the defined daily rate. If time charter contract is considered for the simulations, the charter cost is calculated through a similar approach to the total CTV charter cost. In this case, the jack-up charter cost is considered for each day of the simulations, considering the base rate is that updated each year. The demurrage cost for time charter is defined as '0', due to the fact that the vessel is always under a contract and extension will not be available. The total jack-up charter cost for time charter contract can be calculated by the equations below,

$$Annual\ jack-up\ charter\ cost = Jack-up\ daily\ charter\ cost * 365 \qquad \text{Equation 42}$$

$$Total\ jack-up\ charter\ cost = \sum_{i}^{y} Annual\ jack-up\ charter\ cost_i \qquad \text{Equation 43}$$

If spot charter is considered in the simulations, the total jack-up charter rate calculated becomes complex. In the repair simulation block, the time steps that the jack-up vessel arrives at the offshore wind farm and leaves the site when all the O&M tasks are completed, are recorded. If all the O&M tasks are completed within charter period, the total jack-up charter cost for the particular charter is,

$$Single\ charter\ cost = Jack - up\ daily\ charter\ cost * Charter\ period \quad \text{Equation 44}$$

If the jack-up vessel leaves the site after the agreed charter period is completed, demurrage is added to the total charter cost. The regular charter payment is paid continuously until the jack-up vessel leaves the site; in addition, the demurrage is paid between the final day of the agreed charter period and the day that the jack-up vessel leaves the site. For spot charter case, the total charter cost for the particular charter is,

$$Regular\ charter\ cost = Daily\ chart\ rate * (Charter\ Period + Extension) \quad \text{Equation 45}$$

$$Demurrage\ cost = Demurrage\ rate * Charter\ extesion \quad \text{Equation 46}$$

$$Single\ charter\ cost = Demurrage\ cost + Regular\ charter\ cost \quad \text{Equation 47}$$

Due to the uncertainty of failures and the climate conditions, each charter may have different length and therefore, single charter costs may vary. The summation of all the single charter costs is equal to the jack-up charter cost. The daily charter rate and the demurrage rate are subject to change depending on the 'annual increase' value. At this stage, it is important to highlight that the daily and demurrage rates are considered when the vessel actually arrives at the site. For instance, if the jack-up vessel is chartered in December with a mobilisation period of 6 months, the jack-up vessel will be at the site in June; therefore, summer daily charter and demurrage rates will be considered in this particular case. On the contrary, if the jack-up vessel is charter in June with a mobilisation period of 6 months, the jack-up vessel will be at the site in December; therefore, winter daily charter and demurrage rates will be considered.

$$Total\ jack - up\ charter\ cost = \sum_{i}^{n} Single\ jack - up\ charter\ cost_i \quad \text{Equation 48}$$

where $Single\ jack - up\ charter\ cost_i$ is the charter cost of ith charter contract, n is the total number of charters within simulation period. At the end, the total charter is,

$$Total\ charter\ cost = Total\ jack - up\ charter\ cost + Total\ CTV\ charter\ cost \quad \text{Equation 49}$$

4.4.6.3 Calculation of the total mobilisation cost

The mobilisation cost is considered for the jack-up vessel, and only if the jack-up charter contract type is spot charter. The mobilisation cost for the CTVs and for the jack-up vessel under time charter contract is assumed as '0'. In the time charter case, it is deemed that O&M fleet is always available and the offshore wind farm developed is not dependent on external factors in the planning process. The mobilisation cost is considered for the scenarios that the jack-up vessel is chartered from spot market. Due to uncertainty and variability, the mobilisation cost is also calculated separately for each charter contract.

$$Total\ mobilisation\ cost = \sum_{i}^{n} Single\ jack-up\ mobilisation\ cost_i \qquad \text{Equation 50}$$

where $Single\ jack-up\ mobilisation\ cost_i$ is the mobilisation cost of ith charter contract, n is the total number of charters within simulation period.

4.4.6.4 Calculation of the total fuel cost

The fuel cost of the CTV operations are calculated through the summation of the 'travel time' for each day. In the repair simulation block, the 'travel time' values of each CTV is recorded. In the cost specific attributes section, the fuel consumption of the CTV are defined. Considering the annual increase in the fuel cost, the total CTV fuel cost is calculated by the equations below;

$$CTV_{n,d}\ daily\ fuel\ consumption = Travel\ time_{n,d} * Fuel\ consumption_n \qquad \text{Equation 51}$$

$$Annual\ CTV\ fuel\ consumtion = \sum_{n}^{m} \sum_{d=1}^{365} CTV_{n,d}\ daily\ fuel\ consumption \qquad \text{Equation 52}$$

$$Total\ CTV\ fuel\ cost = \sum_{i}^{y} Annual\ CTV\ fuel\ consumtion_i * Fuel\ Cost_i \qquad \text{Equation 53}$$

In the equations above, the $Fuel\ consumption_n$ is the fuel consumption value of the nth CTV, $Travel\ time_{n,d}$ is the total travel time of the nth CTV during dth day of the year. The $CTV_{n,d}\ daily\ fuel\ consumption$ is the total fuel consumption of the nth CTV during dth day of the year. m is the number of CTVs in the O&M fleet. $Annual\ CTV\ fuel\ consumtion_i$ is the total fuel consumption of during the year i, y is the length of simulations in terms of year. $Fuel\ Cost_i$ is the fuel cost in the year i.

With regard to jack-up vessel, the time-steps that the O&M activities are performed are stored in the repair simulation block. From the operational time-step information, the days that the jack-up vessel is utilised can be identified. The charter length is also required to calculate the jack-up vessel fuel cost. The days that the vessel is not in operation are considered to be days spent at the loading port. Since the daily fuel consumption rates in operation and in port are defined in the vessel specification block, the multiplication of the days in port and in operation by the daily fuel consumption rates provides the total fuel consumption value associated with the jack-up vessel. The total jack-up vessel fuel cost can be calculated by;

$$Total\ fuel\ consumption\ in\ port_i = Days_{p_i} * Fuel\ consumption\ in\ port$$ Equation 54

$$Total\ fuel\ consumption\ in\ operation_i = Days_{o_i} * Fuel\ consumption\ in\ operation$$ Equation 55

$$Total\ fuel\ consumtion_i = Total\ fuel\ consumption\ in\ port_i + Total\ fuel\ consumption\ in\ operation_i$$ Equation 56

$$Total\ CTV\ fuel\ cost = \sum_{i}^{y} Total\ fuel\ consumtion_i * Fuel\ Cost_i$$ Equation 57

where $Days_{p_i}$ and $Days_{o_i}$ are the number of the days spent in port and in operation in the year i. $Total\ fuel\ consumption\ in\ port_i$ is the total jack-up fuel consumption value during the vessel stays at the port in the year i. $Total\ fuel\ consumption\ in\ operation_i$ is the total jack-up fuel consumption value during the vessel performs an O&M activity in the year i. $Total\ fuel\ consumtion_i$ and $Fuel\ Cost_i$ are the total jack-up vessel fuel consumption and fuel price during the year i. The total fuel cost is the summation of the total CTV fuel cost and the total jack-up fuel cost.

$$Total\ fuel\ cost = Total\ jack-up\ fuel\ cost + Total\ CTV\ fuel\ cost$$ Equation 58

4.4.6.5 Calculation of the total staff cost

The total staff cost is also calculated for CTVs and jack-up vessel separately. The CTV staff cost is a continuous cost similar to the CTV charter cost. The CTV charter cost is paid regardless of the CTV usage. The CTV charter cost has two contributors; CTV crew cost and CTV O&M technician cost. The annual cost of these teams are defined in the cost specific attributes section with the specific 'annual increase' values. Therefore the total CTV staff cost is,

$$Annual\ technician\ cost_i = Number\ of\ technicians * Technician\ annual\ cost_i$$ Equation 59

$$Annual\ crew\ cost_i = Number\ of\ crew * Crew\ annual\ cost_i \quad \text{Equation 60}$$

$$Annual\ CTV\ staff\ cost_i = Annual\ crew\ cost_i + Annual\ technician\ cost_i \quad \text{Equation 61}$$

$$Total\ CTV\ staff\ cost = \sum_{i}^{y} Annual\ CTV\ staff\ cost_i \quad \text{Equation 62}$$

where $Technician\ annual\ cost_i$ and $Crew\ annual\ cost_i$ are the annual costs within year i. $Annual\ crew\ cost_i$ and $Annual\ technician\ cost_i$ are the total crew and O&M technician costs in the year i, respectively.

The total jack-up staff cost comprise of the crew cost, the O&M technician cost, and the management team cost. However, if the jack-up vessel is chartered from the spot market, the total jack-up staff cost is considered in the daily charter rates. This is because, the staff required in the jack-up operations have to be specialised due to the high complexity of the O&M activities. When the spot charter periods are taken into account (~1month or less), employing a specialised technician/crew is assumed to be significantly difficult. Therefore, crew and technicians are assumed to be provided by the vessel owner. Regarding management team, it is a generic practice in shipping industry to have a separate person/team, who is only responsible for the vessel management. However, the vessel is managed by the vessel owner, since the charterer has no responsibility after the jack-up vessel leaves the site. Therefore, the management team costs are assumed '0' for the spot charter scenarios.

On the other hand, if the vessel is chartered for a longer period, it is important to have the control of the crew and technicians. It is also important to arrange the crew, supply and provisions for the vessel, therefore a person/team is required for the vessel management. All the staff costs are independent from the vessel utilisation, since it is charterer's risk to charter the vessel for longer periods. Therefore, the total jack-up cost can be calculated by the equation below,

$$Annual\ technician\ cost_i = Number\ of\ technicians * Technician\ annual\ cost_i \quad \text{Equation 63}$$

$$Annual\ crew\ cost_i = Number\ of\ crew * Crew\ annual\ cost_i \quad \text{Equation 64}$$

$$Annual\ management\ cost_i = Size\ of\ management\ team * Management\ annual\ cost_i \quad \text{Equation 65}$$

$$\begin{aligned}&Annual\ jack-up\ staff\ cost_i\\&= Annual\ crew\ cost_i + Annual\ technician\ cost_i\\&+ Annual\ management\ cost_i\end{aligned} \quad \text{Equation 66}$$

$$Total\ jack-up\ staff\ cost = \sum_{i}^{y} Annual\ jack-up\ staff\ cost_i \quad \text{Equation 67}$$

where $Technician\ annual\ cost_i$, $Crew\ annual\ cost_i$, and $Management\ annual\ cost_i$ are the annual costs within year i. $Annual\ crew\ cost_i$, $Annual\ technician\ cost_i$, and $Annual\ management\ cost_i$ are the total crew, O&M technician, and management team costs in the year i, respectively. The total staff cost is equal to the summation of the total CTV staff cost and the total jack-up staff cost.

$$Total\ staff\ cost = Total\ jack-up\ staff\ cost + Total\ CTV\ staff\ cost \quad \text{Equation 68}$$

4.4.6.6 *Calculation of the total fixed cost*

The total fixed costs are calculated on an annual basis. The fixed costs are modelled in order to cover the expenses, which may not be considered in the other cost attributes such as insurance, port expenses, infrastructure improvements, etc. The total fixed costs for CTVs and jack-up vessel are modelled separately as in the equations below,

$$Total\ CTV\ fixed\ cost = \sum_{i}^{y} Annual\ CTV\ fixed\ cost_i \quad \text{Equation 69}$$

$$Total\ jack-up\ fixed\ cost = \sum_{i}^{y} Annual\ jack-up\ fixed\ cost_i \quad \text{Equation 70}$$

$$Total\ fixed\ cost = Total\ CTV\ fixed\ cost + Total\ jack-up\ fixed\ cost \quad \text{Equation 71}$$

where $Annual\ CTV\ fixed\ cost_i$ and $Annual\ jack-up\ fixed\ cost_i$ are the fixed costs in the year i. y is the length of simulations.

4.4.6.7 *Calculation of the total dry-dock cost*

The total dry-dock cost is considered only for the scenarios, in which the jack-up vessel is chartered for time charter. The dry-docking model is based on the survey requirements report prepared by DNV (2011). The survey rules show that two bottom surveys are required during each five-year and the interval between two bottom-surveys cannot exceed 36 months. It is also mentioned that the first bottom survey should be carried out when the age of vessel is 5. Considering the information on DNV (2011), the dry-dock operations are modelled in a way that the first dry-dock operations is performed when the vessel is 5 years of age. The subsequent dry-dock operations of the jack-up vessel are performed with 2.5 year intervals (Table 17). In this context, the vessel age and the simulation period have a crucial role in the dry-dock cost calculations. For instance, if a brand new vessel chartered for 5 years, the dry-dock cost will be zero, because the first dry-dock operation will be 5 years after. On the other hand, if the vessel is 20 years of age and the simulation length is 10 years, 4 dry-dock operations have to be performed by the charterer. The dry-dock period (~15 days) is negligible compared to the simulation period (~5 years); therefore, the dry-dock operations are considered only for cost calculations.

Table 17: Jack-up dry-dock operations

Vessel age	Dry-dock
5	✓
7.5 (8)	✓
10	✓
12.5 (13)	✓
15	✓
17.5 (18)	✓
20	✓
22.5 (23)	✓
25	✓
27.5 (28)	✓
30	✓
32.5 (33)	✓
35	✓

4.4.6.8 Calculation of the total sub-charter cost

The total sub-charter cost is considered only for the scenarios, in which the jack-up vessel is chartered for time charter. Sub-charter means that the jack-up vessel can be chartered to the third parties in order to compensate the costs and increase the total revenue. The charter rates for the sub-charter model are same as the spot market charter rates. Therefore, the jack-up vessel is chartered from vessel owner with a time charter rate, and it is sub-chartered to the third parties with a spot market charter rate. It is assumed that the sub-charter operations do not disturb the O&M activities of the offshore wind farm developer. The total sub-charter cost is calculated by,

$$Annual\ sub-charter\ cost_i = Sub-charter\ rate_i * Number\ of\ charters * Number\ of\ days\ in\ charter \qquad \text{Equation 72}$$

$$Total\ sub - charter\ cost = \sum_{i}^{y} Annual\ sub - charter\ cost_i \qquad \text{Equation 73}$$

Although the sub-charter operations are considered as a cost attribute, the cost associated with them is reflected as negative cost, which basically decreases the total O&M cost.

4.5 Decision making and additional outputs

In addition to what has been discussed so far, the methodology provides additional outputs in order to support the optimised decision. This is required because, making the decision only by considering the cost attributes may lead the offshore wind farm developers to wrong directions. In this context, the cost is per unit production (O&M cost/MWh) is one of the key aspects, because it demonstrates the added value of the extra O&M activity on the power production. Theoretical total revenue is also calculated to show the maximum revenue that can be gained from the power production if the turbines produce power without downtime. The theoretical total revenue and the theoretical power production values include the effect of weather. The revenue loss value is calculated considering the total O&M cost, the total revenue and the theoretical total revenue. Basically, the revenue loss value shows the financial difference between the current situation and the best situation. In this respect, the scenario with the lowest revenue loss is the optimum solution. The revenue loss is,

$$Revenue\ loss = \frac{Theoretical\ total\ revenue + Total\ O\&M\ cost - Total\ revenue}{Theoretical\ total\ revenue} \qquad \text{Equation 74}$$

The availability of the offshore wind farm is a well-known measure that show the power productivity of the offshore wind farm. In the methodology, the power-based availability is calculated; which is the proportion of the power production to the theoretical power production,

$$Availability = \frac{Power\ production}{Theoretical\ power\ production} \qquad \text{Equation 75}$$

In order to demonstrate the optimum composition of the O&M fleet, the jack-up vessel charter length and the jack-up vessel contract type and CTV fleet composition are presented. In addition, the jack-up vessel utilisation is calculated in order to show the average usage of the jack-up vessel during the charter period. The jack-up vessel utilisation is calculated by dividing the number of time steps that the jack-up vessel is employed to the number of time steps in the charter period;

$$Jack - up\ vessel\ utilisation = \frac{\sum Time\ steps_{used}}{\sum Time\ steps_{charter\ period}} \qquad \text{Equation 76}$$

In the transit time block, average idle time, productive time and travel time values are calculated specifically for CTV operations. In addition, average CTV accessibility and average CTV utilisation is calculated. In the average CTV accessibility calculation the actual accessibility is taken into account, which means that the 'minimum working limit' value, the distance between the port and the offshore wind farm are also considered. For instance, if the distance is between the port and the offshore wind farm is significantly long, the CTVs may only able to access in particular days, even though the climate conditions theoretically do not completely cease the operations. The average utilisation of the CTVs is the proportion of the total number of days that the CTVs are allocated to a repair and the length of simulations.

$$CTV\ utilisation = \frac{\sum Days_{allocated}}{\sum Days_{simulation\ length}} \qquad \text{Equation 77}$$

If a CTV is allocated even to a single repair, this particular CTV is considered as employed. In order to demonstrate the operational efficiency of each CTV, average technician usage and average turbine visit values are calculated. Additional detail regarding CTV travel times is provided through the calculation of average travel time between the port and the offshore wind farm and average internal travel, which is the time spent for the travels between the turbines.

For the failure statistics, the MTTR values and the average number of failures associated with each turbine component are also demonstrated as an output. MTTR values show the influence of delays in the O&M activities. In an imaginary case that the failure reaction time is zero, the MTTR values have to be equal to the repair periods defined prior to the simulations. The average number of failures is beneficial to identify the critical components that cause turbine shut down and cease the power production.

4.6 Assumptions of the developed model

In any research, it is usually the case that certain assumptions and limitations are present to enable the implementation of the research study. It is important to explain these aspects clearly to the reader. The limitation and assumptions of the developed model are described below;

- Failures occur at any time during a simulated shift but repairs will only begin during the subsequent shift. Failures are currently simulated independently and are not influenced by current climate. Repair returns the component to 'as good as new' state.
- Repairs performed using different vessel categories are considered independently. Assuming only single jack-up vessel is commissioned at once due to expense involved, more expensive vessels are never used for alternative failure categories.
- Currently, CTVs are allocated dynamically during operating shift. It is aimed to sustain productivity at highest level; therefore capability of completing repair task in a single shift is the most important consideration in CTV allocation. In addition to operability limitations, CTVs are also limited by working shift and daylight hours; CTVs can travel without daylight, but O&M activity can be started only within daylight hours.
- Jack-up repairs are performed sequentially as soon as a failure of this category occurs. After the first failure is simulated, a vessel is mobilised. Once mobilisation time is completed, repairs can be performed subject to wind speed and wave height conditions. The jack-up operation is determined by wave height and wind speed at sea level while the main repair operation is performed subject to wind speed criteria at hub level.
- If there are remaining hours where work can be performed after corrective maintenance is completed, preventive maintenance is carried out until the technicians are picked up from the turbine; turbines then go back online.
- All turbines in wind farm are assumed to have same specification.
- Climate is assumed to be uniform between offshore wind farm and O&M port. Wind speed is calculated additionally at 10m height from sea level for the vessel related operations regardless of the actual observation height.
- Maintenance tasks are classified as either preventive maintenance or corrective maintenance, condition based maintenance is not considered directly as it is assumed to fall under the corrective maintenance failure rate.

- Tasks taking longer than the operating shift are automatically split over shifts. The repair time required at the end of a shift is recorded and becomes new time requirement at beginning of next shift.
- When a maintenance team is allocated to a wind turbine, the priority is finalising the corrective maintenance task as soon as possible. When the failure is repaired, same technician team continues to do scheduled maintenance (if required), otherwise stays in the wind turbine. The teams are not allocated to different wind turbines in a single shift.
- Headings are given in terms of the relative heading of the waves compared with that of the vessel track (head seas = 180º; following seas = 0º; starboard beam seas = 90º, port beam = 270º etc.). When compared with the ship's stability characteristics in still water, following waves can lead to a considerable reduction of the transverse stability and unacceptable large roll angles can be the observed. Beam seas can cause capsizing due to high roll motions. In addition to the stability and manoeuvrability issues, current added resistance calculations with beam and following seas are not as accurate as the added resistance calculations with heading seas. Therefore, it is expected that CTVs will travel in head seas.
- While a CTV is traveling in waves, skipper can keep the power constant and decrease the speed or keep the speed constant and increase the power. In the transit model block, the power and thrust of the CTVs will be kept constant and speed will change with the influence of waves. This assumption will lead to constant fuel consumption with a single interval. It should not be forgotten that the total fuel consumption of CTVs will vary with the influence of fluctuations on the total travel time.

4.7 Chapter summary

In this chapter, the novel OPEX model and O&M fleet optimisation methodology for offshore wind farms is proposed and described in detail. The proposed methodology is explained in two major sections. Firstly, the input sections, the requirements and information that are processed are explained. In the second section, the analysis and calculation blocks are introduced. In these blocks, the information passed by the input sections is arranged, analysed, simulated, and the major outputs are demonstrated.

In the simulation sequence, artificial climate datasets are generated from historical climate observations. In order to eliminate the uncertainty of the climate on the simulation results, it is intended to generate diverse artificial datasets, which preserve the generic characteristics (distribution, weather window, correlation) of the original dataset. The vessel operability analysis and transit time calculations are performed considering the generated artificial climate datasets, the vessels in the vessel pool, and the specifications of these vessels. In order to identify the failures, time domain Monte-Carlo simulations are performed in the failure simulation block. In this context, turbine failures are dependent on the turbine component failure rates which are also time dependent as well as the configuration of the turbines. In the repair simulation block, the actual O&M activities are simulated considering the failure time steps, number of simultaneous failures, type of vessels and the number of O&M technicians required for the repair activity, vessel availability, vessel operability, and the artificial climate datasets. In the cost calculation block, all the outputs of the previous analysis/calculation blocks are synthesised with the cost specific attributes; and the final results are calculated to compare and identify the most cost effective scenario.

At the end of Chapter 5, how the decision is made is explained and the additional outputs are presented. In the following section, case studies are carried out in order to validate the structure of the methodology and demonstrate the accuracy of the analysis results.

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5 Case Study – Identification of the Optimum O&M Fleet

5.1 Chapter outline

In the previous section, the proposed methodology is explained in details. In Chapter 5, the application of the proposed methodology is presented to validate the simulation approach. In order to preserve the consistency in the thesis, the arrangement of Chapter 5 has remained similar to the arrangement of Chapter 4. Figure 38 broadly explains the content of each section in Chapter 5 and demonstrates the flow of the simulation algorithm. The case study section starts with the presentation of the input sections (green boxes in Figure 38): climate observations, vessel pool, vessel specification, operational decisions, vessel chartering, wind farm/turbine specific attributes, and cost specific attributes. As explained in Chapter 4, these parameters are necessary for the operational simulations. After identifying the input parameters, the analysis/calculation sections (red boxes in Figure 38): climate generation, vessel operability and transit time calculation, failure simulation, repair simulation, power calculation, cost calculation blocks are described by synthesising the information defined in the input sections.

A case study, in which 140-turbine wind farm configuration is taken into account, is investigated and operational simulations are performed in Chapter 5. This wind farm configuration reflects a Round 2 wind farm in the UK. The results of the case study are presented and the chapter summary is provided at the end in order to summarise the work that is performed in Chapter 5.

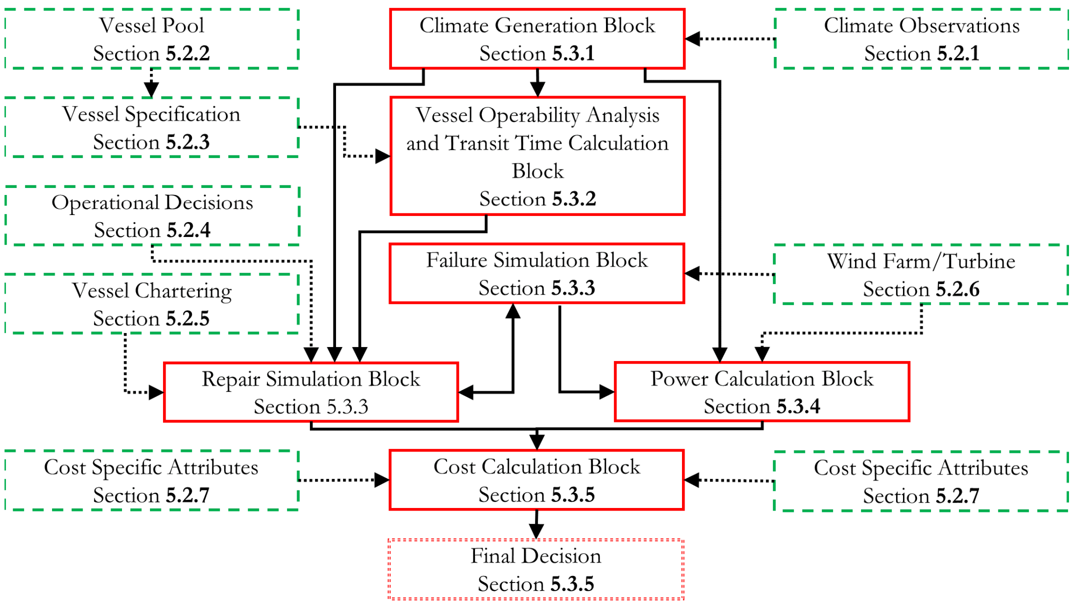

Figure 38: Simulation algorithm flow

5.2 Data collection, initial analysis and interpretation

5.2.1 Climate observations

Figure 39 shows the simulation phase, which is explained in the section. In order to demonstrate a clear framework, the box associated with this section is highlighted and other boxes are made transparent. In the case study, the climate observations from FINO1 research platform is taken into account. The FINO1 observation and research platform was brought into service in 2003. Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (BMUB) decided the construction of three research platforms (FINO1- FINO2 - FINO3) in the North Sea and the Baltic Sea to support the offshore wind projects in the planning stage. Research and Development (R&D) Centre of Kiel University of Applied Sciences (Forschungs und Entwicklungszentrum Fachhochschule Kiel GmbH) has been managing the FINO1 observation platform since 2012.

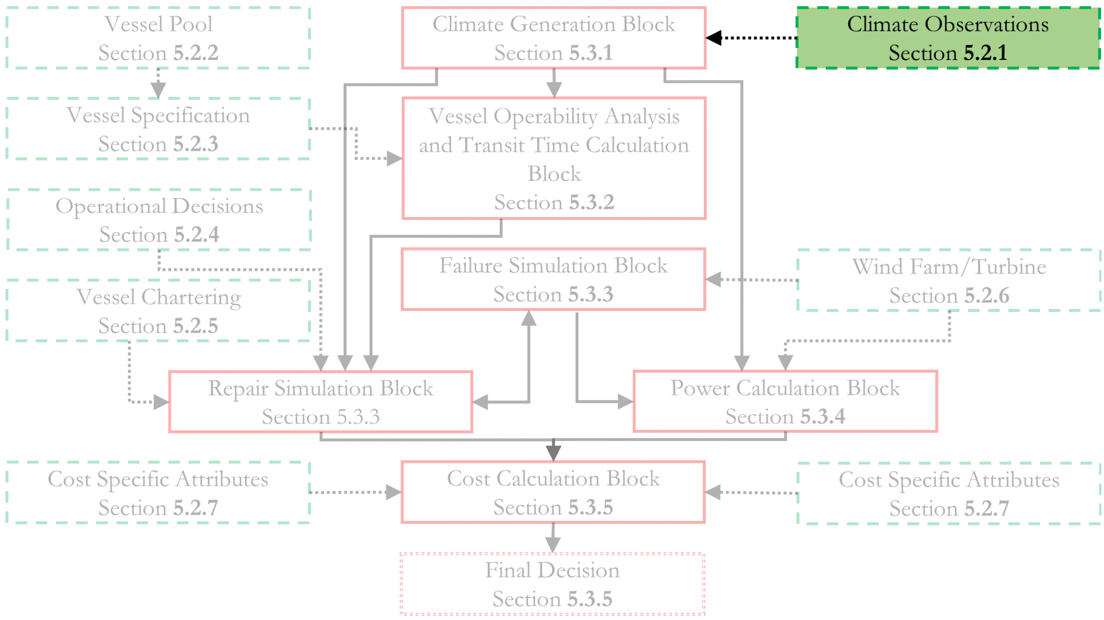

Figure 39: Definition of simulation phase

As shown in Figure 40, FINO1 is located 45 kilometres to the north of Barkum Island in the North Sea (FINO, 2014). The coordinates of the location are as follows: N 54^0 00' 53.5" E 6^0 35' 15.5". The wind measuring mast is over 80 m in height, and the maximum height of the wind measurements is 103 m above the sea level. In addition to wind speed observations, wind direction, air temperature, atmospheric pressure, atmospheric humidity, atmospheric density, rainfall, total radiation, UV insolation, visibility, number of lightning strokes, water level, current (speed and direction at various water depths), sea conditions (wave height, wavelength, wave direction), water layers, water temperature, oxygen content, salt content are also recorded and free access is provided for the scientific institutions inside the EU. However, it is identified that some of the observations are either missing or incomplete due to unknown reasons.

Figure 40: FINO observation platforms (FINO, 2014)

5.2.1.1 *Wind speed, wave height, and wave period observations*

In the case study, a climate dataset, which consists of hourly wind speed, wave height, and wave period values for a period of 5 years (2004-2008), is taken into account. The wind speed observations are recorded at 33m height from sea level. The maximum, the minimum, and the mean values for each year of the individual datasets are presented in Table 18. In addition, the annual distribution of the wind speed, wave height, and wave period datasets for each individual year can be seen in Figure 41-Figure 43, respectively. It can be seen that the generic characteristics of the distributions are similar for each year, even though minor variations are noticed between the years.

Table 18: Maximum, minimum, and mean of the annual datasets

	Wind Speed (m/s)			Wave Height (m)			Wave Period (sec)		
	Maximum	Minimum	Mean	Maximum	Minimum	Mean	Maximum	Minimum	Mean
Year 1	24.89	0.39	8.56	5.48	0.17	1.46	8.60	2.50	4.66
Year 2	28.81	0.49	8.82	6.32	0.15	1.47	8.80	2.40	4.76
Year 3	29.17	0.42	8.56	9.47	0.17	1.37	10.35	2.25	4.51
Year 4	25.51	0.55	9.11	6.71	0.21	1.59	8.60	2.50	4.68
Year 5	27.83	0.67	9.65	7.25	0.20	1.57	10.90	2.40	4.71

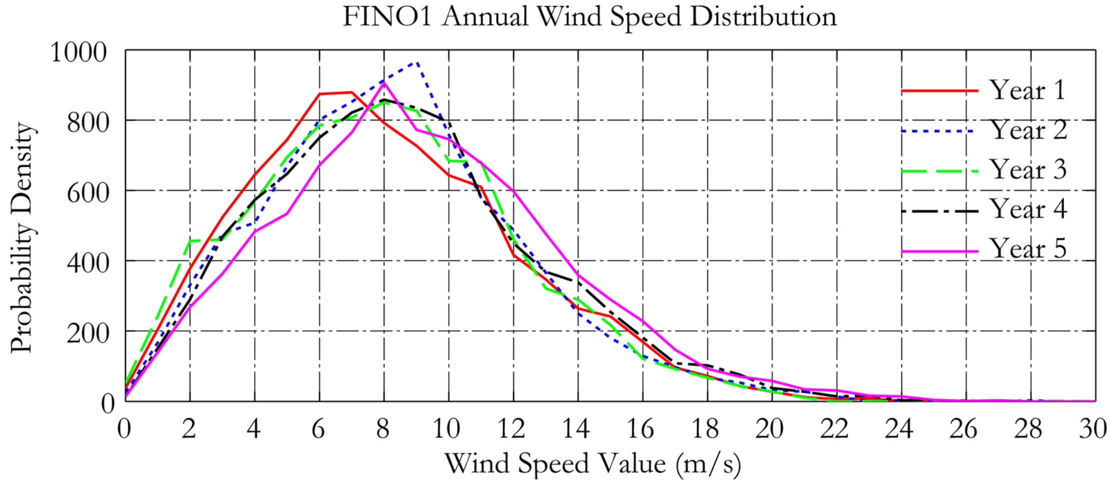

Figure 41: Annual wind speed distributions (FINO1)

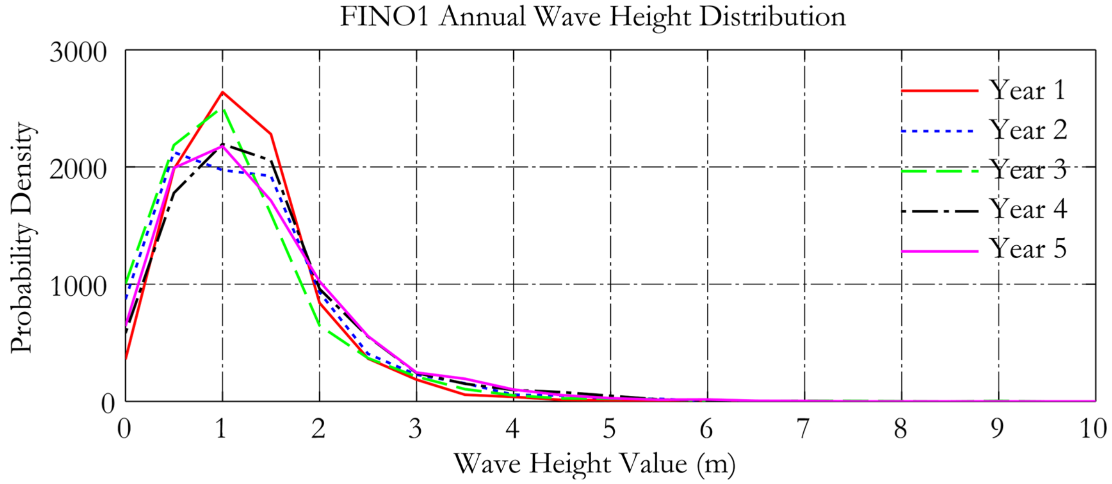

Figure 42: Annual wave height distributions (FINO1)

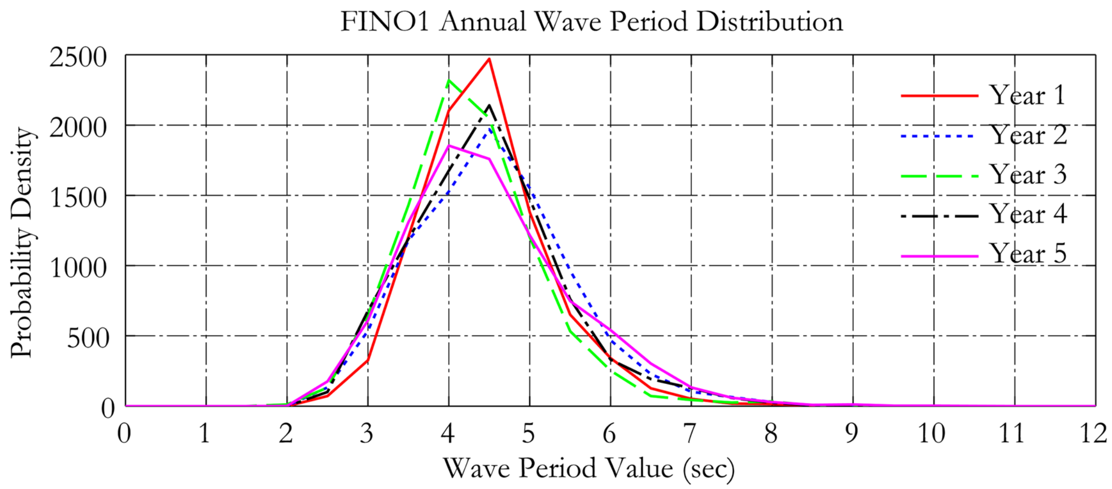

Figure 43: Annual wave period distributions (FINO1)

The autocorrelation function figures are also presented in Figure 44-Figure 46. The vertical red lines in these figures represent the degree of relation between the current value and its lags (past values). Since '0' lag is the current value, the autocorrelation values at '0' lag are '1' in each dataset. The blue horizontal lines in all figures show the 95% significance limit. The autocorrelation function remains significant until a high lag order; therefore, as Dietz (2010) and Evans (2002) stated, partial autocorrelation coefficients are also considered in order to identify the relation within individual datasets (Figure 47-Figure 49). It can be seen that the partial autocorrelation function of the wind speed dataset decays quicker than the partial autocorrelation functions of the wave height and wave period datasets. This means that the relation between time steps is stronger for wave height and wave period than the relation of the wind speed observations.

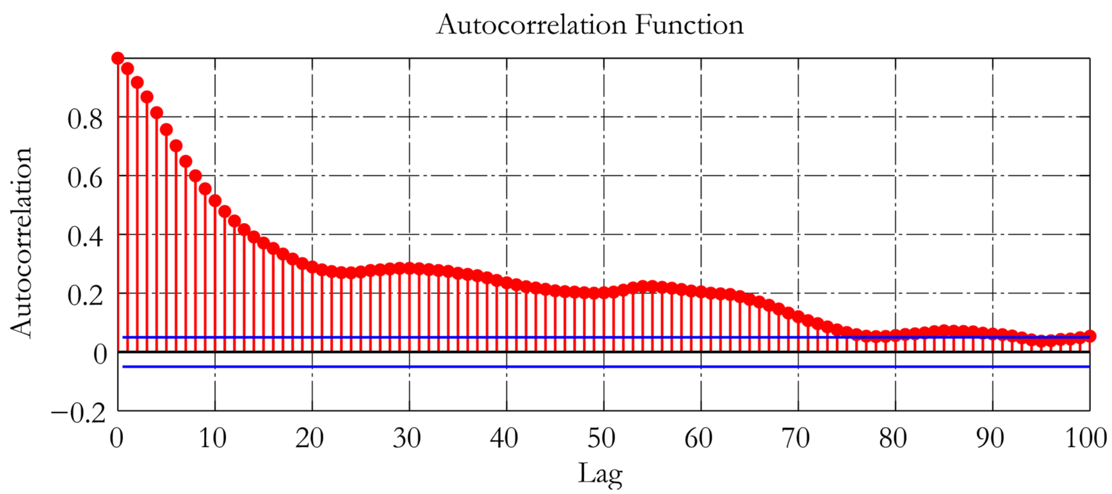

Figure 44: Autocorrelation function for wind speed dataset (FINO1)

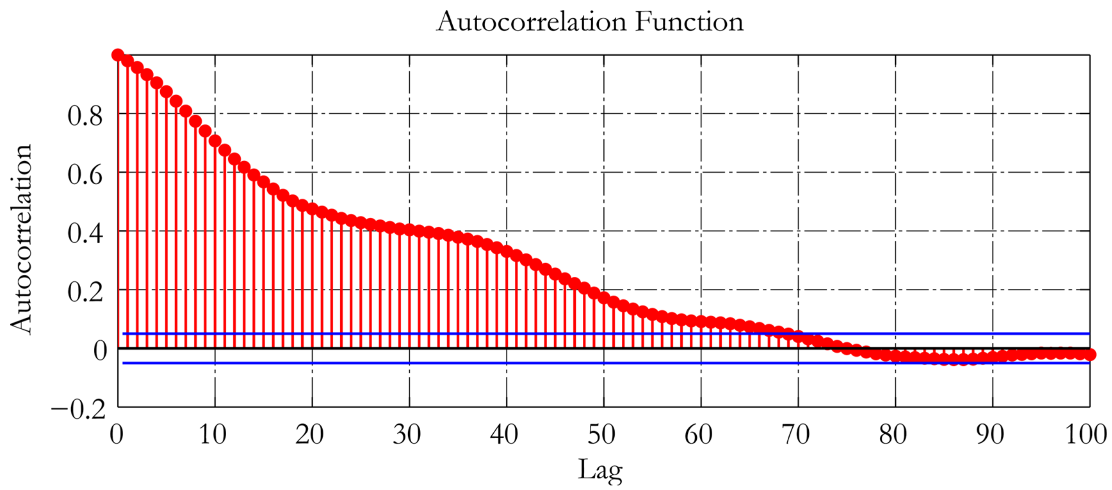

Figure 45: Autocorrelation function for wave height dataset (FINO1)

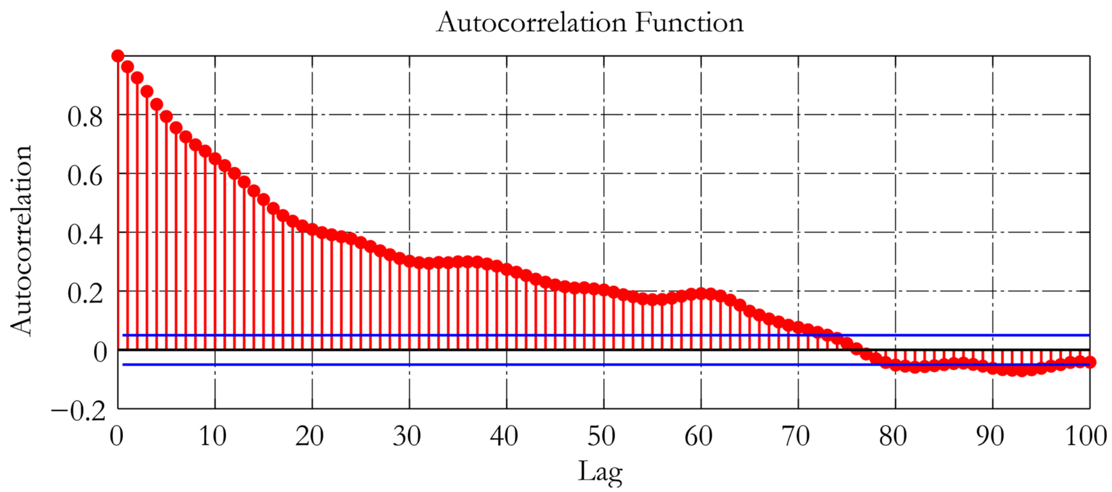

Figure 46: Autocorrelation function for wave period dataset (FINO1)

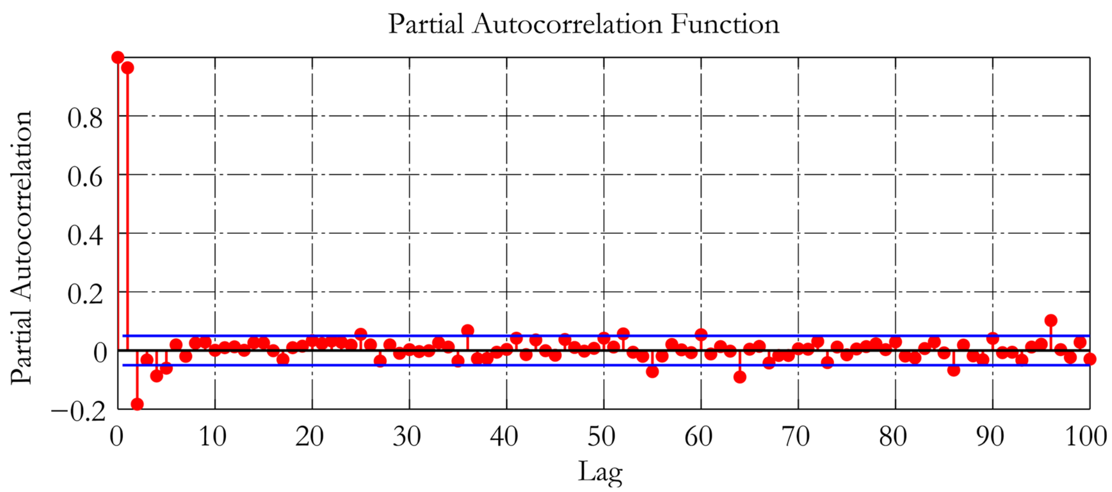

Figure 47: Partial autocorrelation function for wind speed dataset (FINO1)

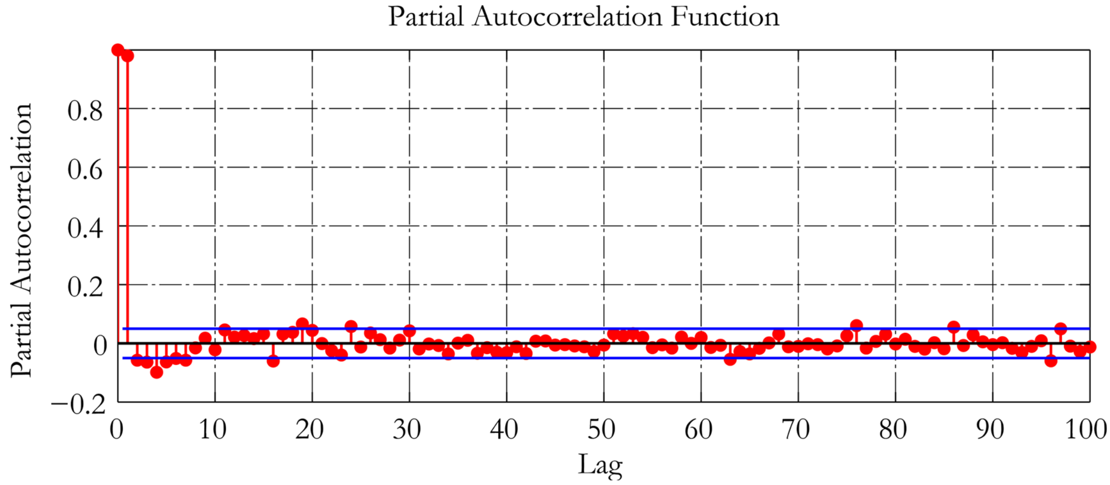

Figure 48: Partial autocorrelation function for wave height dataset (FINO1)

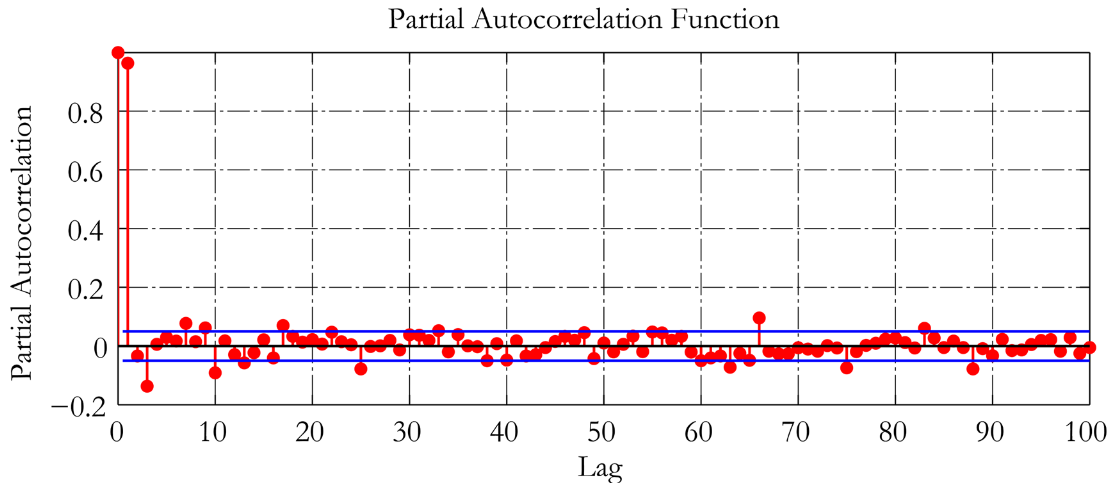

Figure 49: Partial autocorrelation function for wave period dataset (FINO1)

In addition to the annual distribution and correlation illustrations, duration of weather window and monthly average values are shown in Figure 50-Figure 54. Duration of weather window graphs (Figure 50-Figure 51) are created considering the wind speed and the wave height values separately. 5 m/s, 10 m/s, 15 m/s, and 20 m/s wind speed and 0.5 m, 1.0 m, 1.5 m, 2.0 m wave height values are selected to demonstrate the probability of occurrence that the wind speed or wave height values in consecutive time-steps are higher than specified limits. Therefore, the higher the limits become, the less probability of occurrence is experienced. Similarly, the more the number of consecutive time-steps, the less probability of occurrence is experienced.

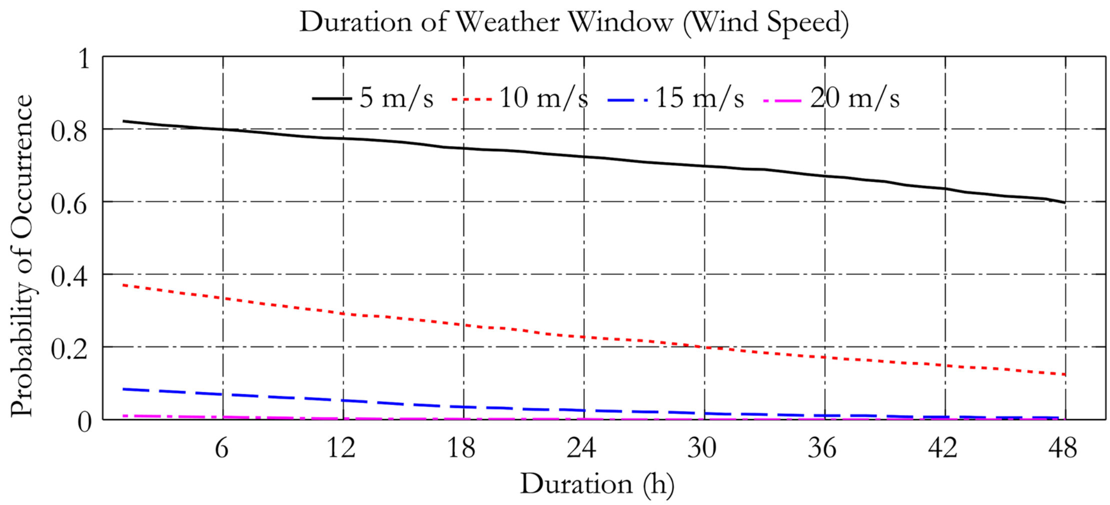

Figure 50: Duration of weather window, considering wind speed (FINO1)

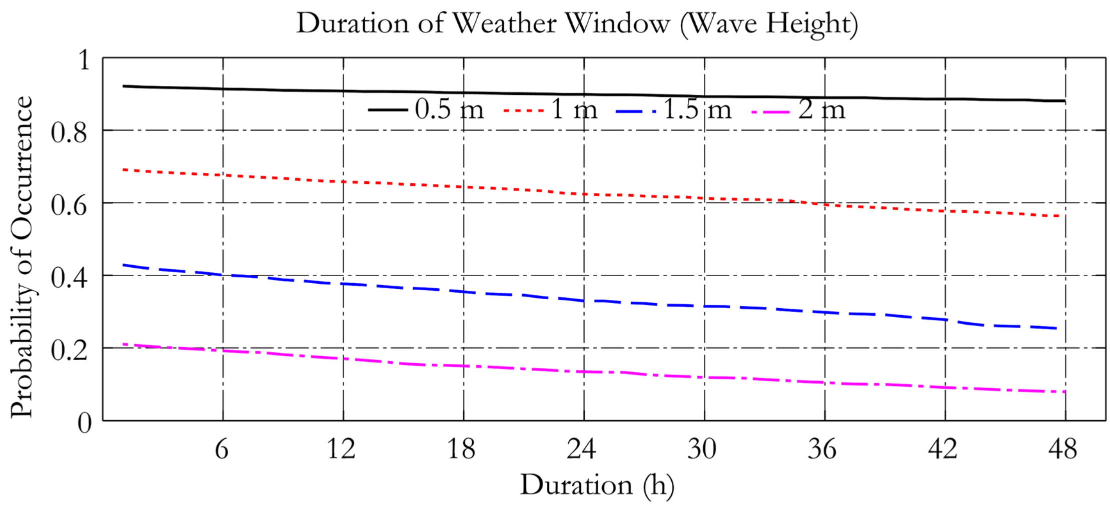

Figure 51: Duration of weather window, considering wave height (FINO1)

The monthly average values in Figure 52-Figure 54 indicate a strong relationship between the average values and the month. It can be seen that the average values in winter (October-April) are higher than the average values in summer (May-September) for each individual dataset. The importance of the wind speed variation within a year can be realised, when the power curve of a wind turbine is investigated as in Figure 55. At this instance, when the wind speed is 7 m/s, a single 5 MW wind turbine can theoretically (excluding any loss) produce 956.7 kW per hour; on the other hand, when the wind speed is 14 m/s, same turbine can theoretically (excluding any loss) produce 4,695 kW per hour, which is very close to the maximum power production value. In this context, the cost of turning a turbine off in winter is significantly higher than the cost of turning a turbine off in summer. The figures in the 'climate observations' section are important to demonstrate the generic characteristics of FINO1 wind speed dataset. They are also crucial to validate the climate generation block. In the climate generation block validation stage, these figures are compared with the figures that are created from the generated datasets for each simulation in order to prove that the generic characteristics of the original dataset are preserved.

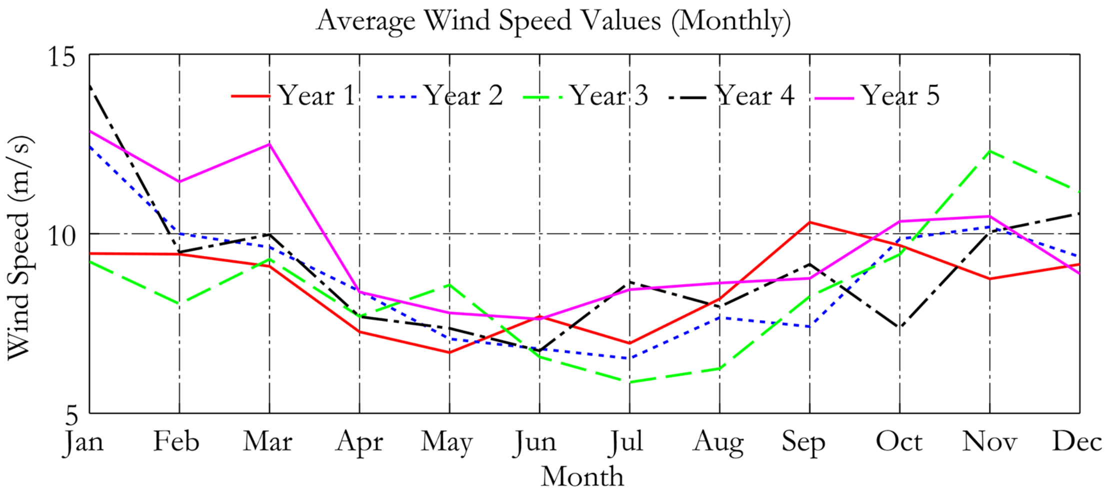

Figure 52: Monthly average wind speed values (FINO1)

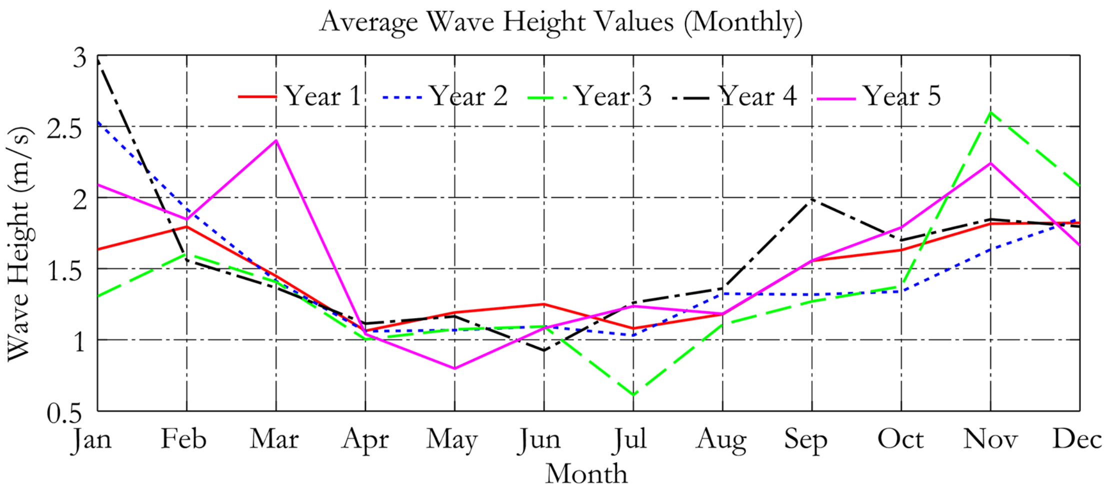

Figure 53: Monthly average wave height values (FINO1)

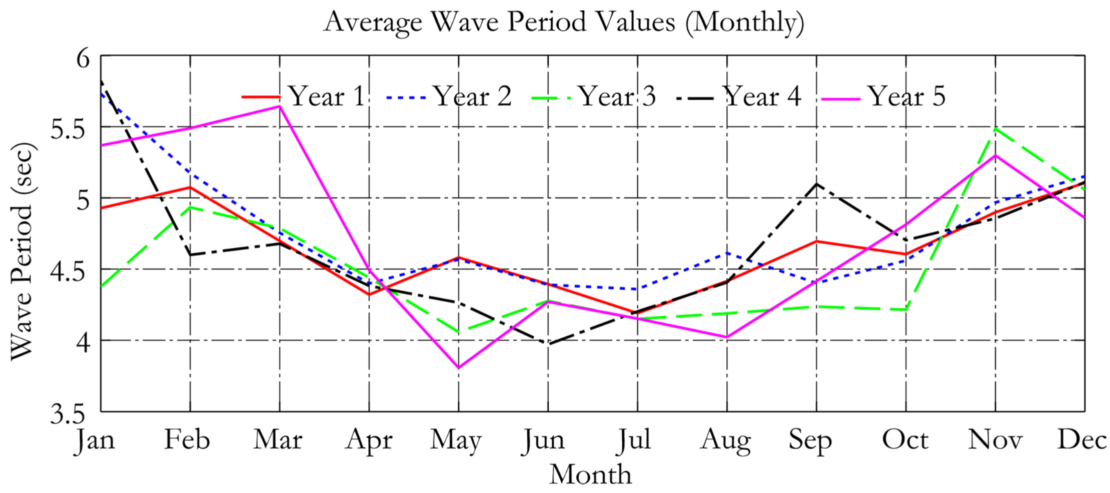

Figure 54: Monthly average wave period values (FINO1)

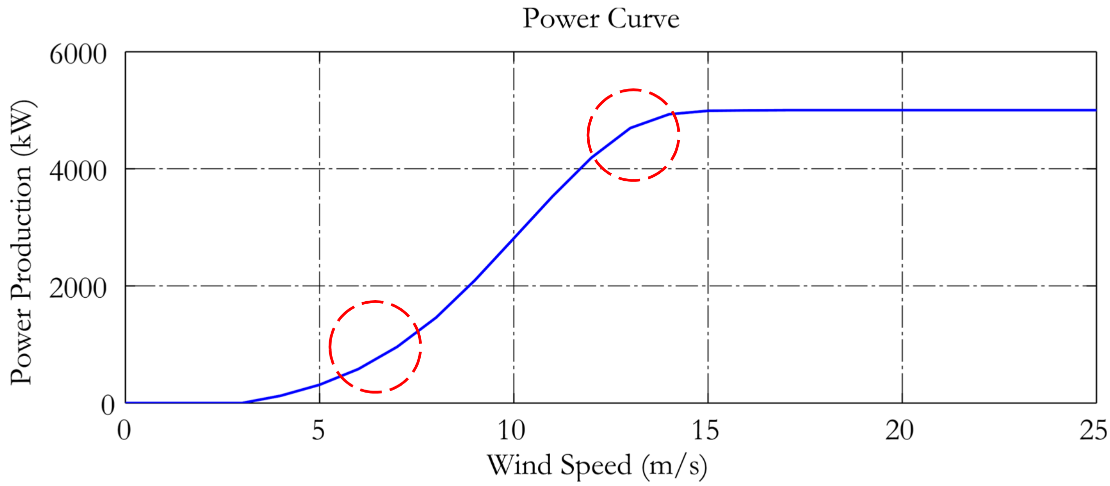

Figure 55: An example power curve of a 5 MW offshore wind turbine

5.2.2 O&M vessel pool

Figure 56 shows the simulation phase, which is explained in the section. In order to demonstrate a clear framework, the box associated with this section is highlighted and other boxes are made transparent. In the O&M vessel pool, 3 different CTV types and their characteristics are presented in the 'Vessel specification' section, are considered. The minimum and the maximum CTV fleet size values are defined as '2' and '10', respectively. Based on the discussions with the industry experts, it is identified that ~5 CTVs are generally utilised in the current offshore wind farms. Considering the size of wind farm in the case study, it is believed that the optimum CTV fleet size value fit within the rage of [2, 10]. At the end of simulations, if the optimum CTV fleet size is identified either '2' or '10', further cases can be simulated for smaller or larger fleets; however these upper and lower limits are set for the initial stage. In the scenarios, all the combinations are taken into account; therefore the optimum O&M CTV fleet can comprise of only a single CTV type or a combination of 3 CTV types. In this context, the climate conditions, operational capabilities, failure rates of the turbine components and the costs of major aspects have significant importance. If the climate conditions are relatively smooth, CTVs with lower operational capabilities can be sufficient to sustain the power production. On the other hand, if the failure rates are significantly high, a faster CTV fleet may be required to minimise the reaction time. In the addition to CTVs, a single jack-up vessel is considered in the O&M fleet in the scenarios; but the chartering strategy varies as explained in the modelling section.

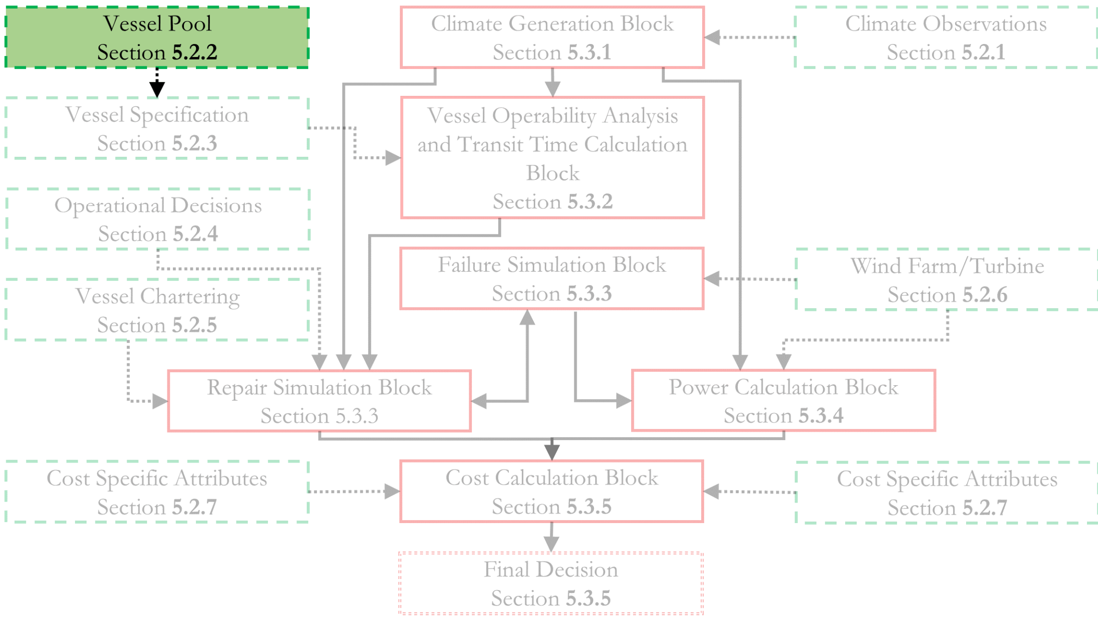

Figure 56: Definition of simulation phase

5.2.3 Vessel specification

Figure 57 shows the simulation phase, which is explained in the section. In order to demonstrate a clear framework, the box associated with this section is highlighted and other boxes are made transparent. The jack-up vessel considered in the case study is 'MPI Resolution', which is built in China under the name of 'Mayflower Resolution' and has been operating for the offshore wind farm industry since she is launched in 2003. The detailed specification can be found in MPI Offshore (2013). As Osborne (2004) stated the building cost of MPI Resolution was £53M in 2003, and its relative value in 2013 based on the historical Retail Prices Index (RPI) is £73.11M. The vessel has 4 Mitsubishi S16R-MPTK main generators with a capacity of 1,920kW at 1,800rpm to supply main power during operations and 2 Mitsubishi S6B-MPTA harbour generators with a capacity of 276kW at 1,800rpm. During O&M activities, it is expected that all the main generators are in production due to the fact that the main 600Mt crane is in use. When the jack-up vessel is in the O&M port, it is assumed that only the harbour generators are in production. The main and the harbour generators have 268.7 litre/hour/unit and 55.7 litre/hour/unit fuel consumption rates, respectively (Mitsubishi Heavy Industries, 2014). Therefore, the daily fuel consumption in operation is 25.79 tons and the daily fuel consumption in port is 2.67 tons for the jack-up vessel. Since, the main power source of the vessel is the generators, it is assumed that the low sulphur marine gas oil is used for the fuel type. Table 19 demonstrates the inputs required for the jack-up vessel simulations.

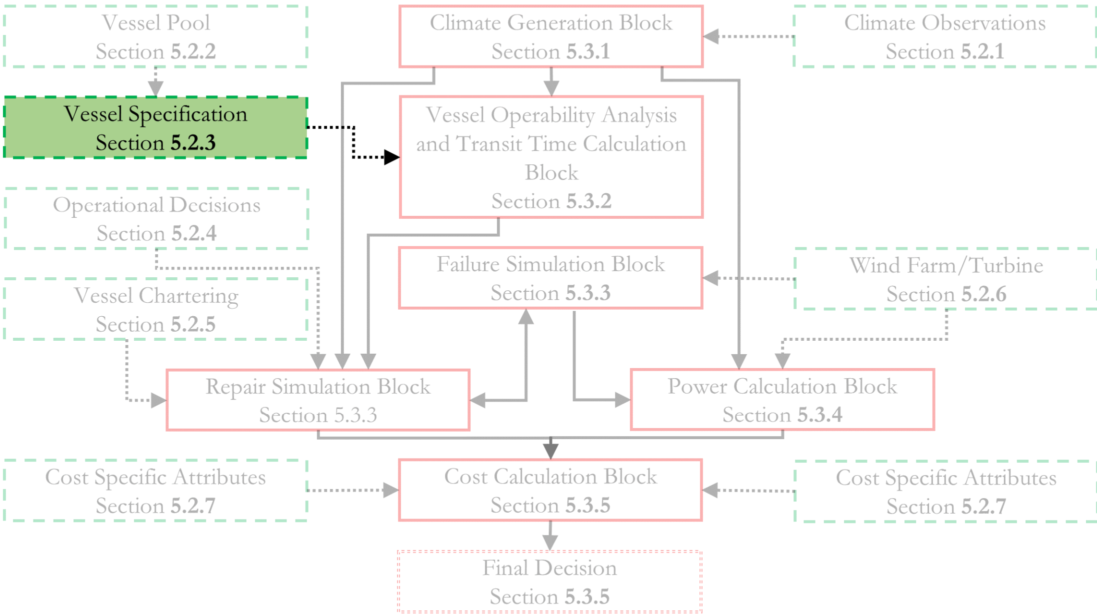

Figure 57: Definition of simulation phase

As stated in the previous section, 3 types of CTVs are investigated in the case study. It is well known that 'Catamaran' type of CTVs dominate the offshore wind market; therefore, all the CTVs are selected as 'Catamaran'. In order to examine the operational capabilities and accessibility performance of different types, it is envisaged that a 'Large' type, a 'Medium' type, and a 'Small' type of CTV are considered in the simulations. In this respect, the CTVs operated by South Boats are taken into account. Their CTV fleet ranges from 13 m to 28 m catamarans. Among their CTV fleet, the CTVs categorised under '26 m WFSV' (Large), '21 m WFSV' (Medium), and '17 m WFSV' (Small) are selected to utilise in the simulations. The technical specifications of '26 m WFSV', '21 m WFSV', and

'17 m WFSV' can be found in South Boats (2014a), South Boats (2014b), and South Boats (2014c), respectively. Table 20 demonstrates the inputs required for the CTV simulations.

Table 19: Jack-up vessel inputs

Input Name	Type	Value	Unit
Wind speed at sea level	Jacking	15.3	m/s
Wave height	Jacking	2.8	m
Wind speed at hub level	Operational	20	m/s
Wind speed at sea level	Survival	36.1	m/s
Wave height	Survival	10	m
Fuel consumption (stationary)	Cost	2.67	$tons/day$
Fuel consumption (operational)	Cost	25.79	$tons/day$
Jack-up/down time	Operational	30	$m/hour$
Vessel age	Cost	11	$year$
Number of crew	Cost	30	$-$
Number of O&M technicians	Operational-Cost	12	$-$
Size of management team	Cost	5	$-$

Table 20: CTV inputs

Input Name		Value		Unit
Vessel name	26 m WFSV	21 m WFSV	17 m WFSV	
Vessel type	Catamaran	Catamaran	Catamaran	$-$
Length overall	26.77	21.01	17.47	m
Length waterline	24.92	19.36	16.02	m
Breadth	9.12	7.30	6.30	m
Breadth demihull	3.52	2.81	2.43	m
Draught	1.38	1.401	1.20	m
Displacement	242	95	53	$tons$
Operational speed	26 knots	27.5 knots	24.5	$knot$
Installed power	2160	2058	1764	kW
Main Engines	2 x MTU 12V-2000-M72	2 x MAN V12-1400	2 x MAN D2862LE432	
Wave height	1.5	1.25	1.0	m
Wind speed	26	22	18	m/s
Fuel consumption	0.5	0.5	0.4	m^3/h
Technician capacity	12	12	12	$-$
Number of crew	3	3	3	$-$

5.2.4 Operational decisions

Figure 58 shows the simulation phase, which is explained in the section. In order to demonstrate a clear framework, the box associated with this section is highlighted and other boxes are made transparent. The distance between turbines in a row is generally the order of 5-10 rotor diameters, and the distance between the rows is generally 7-12 rotor diameters (Patel, 2005, Sun *et al.*, 2012). The largest turbine concepts/trials are close to

150 m rotor diameter (Hameed and Vatn, 2012); Fichaux *et al.* (2011) stated that 20 MW turbines with 250 m rotor diameter can be feasible in the future. Even 250 m rotor diameter with 12 rotor diameter distance is considered, this distance ($250\,m * 12 = 3\,km$) can be travelled by a medium speed (~20 knots) in 5 minutes. When the influence of the weather is taken into account, it is believed that 10 minutes travel time between the turbines in the offshore wind farm can present a real case (Table 21). Considering 10 minutes 'Inter-transit time', it is envisaged that a CTV can perform maximum 4 visits, so the reaction time in emergency situations can be limited to 30 minutes. It should be highlighted that the 'Maximum visit for a CTV' value is an arbitrary value; however the layout of the wind farm has to be modelled in a more comprehensive approach in order to represent current safety practices. It is believed that allocating 2 technicians for ordinary repairs and 4 technicians for more complicated repairs is a reasonable plan to complete the repairs in a single working shift. When the size of the nacelle and the available space in the nacelle are taken into account, the teams more than 4 technicians can slow down the activities due to dense population.

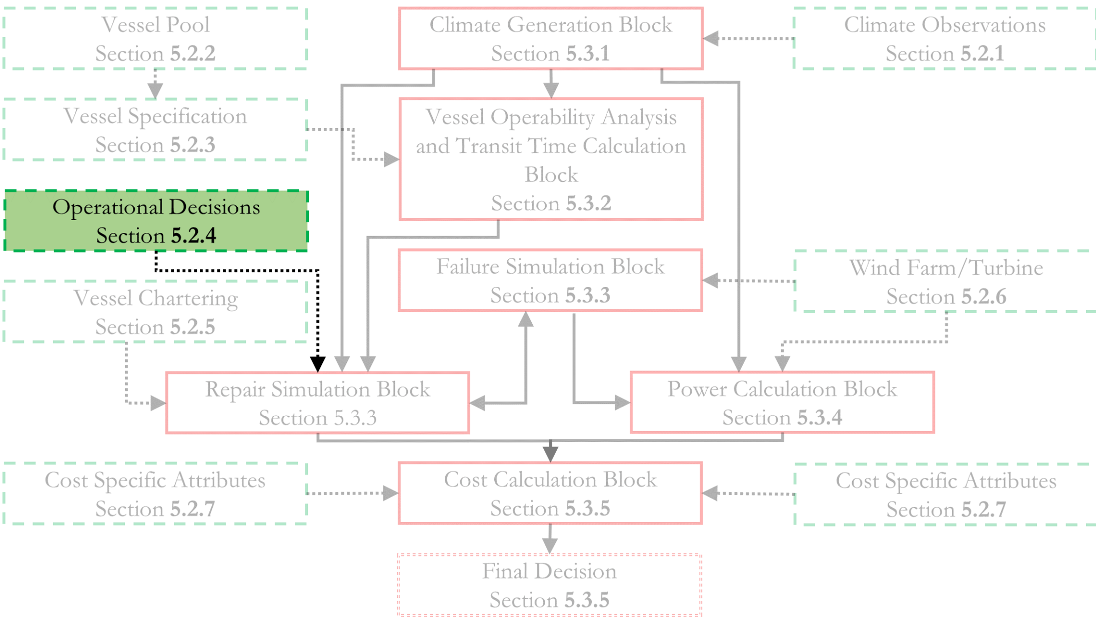

Figure 58: Definition of simulation phase

When the technicians are transferred from a CTV to a turbine, they need to take their equipment to nacelle, climb up internal ladder (or use lift in larger turbines) and sometimes use nacelle crane to transfer the spare parts into nacelle. In this case, they cannot start the actual O&M activity right after they are transferred to a turbine. This is also applicable at the end of a working shift. When all the O&M activities are completed, all the equipment needs to be moved to turbine lower platform and the technicians need to climb down before a CTV picks them up from the turbine. This aspect is modelled as the 'Time to start working' input, which decreases the total productive time in a working shift. Furthermore, it is well known that certain hours need to be spent for the preventive maintenance activities to keep the turbine in a good condition. 57.5 hours is defined as the number of calendar hours for preventive maintenance. Based on the communications with the industry experts, 2 hours limit is defined as the 'minimum working hour'; therefore, if the available productive period in a repair day is shorter than 2 hours, CTVs and technicians stay in the O&M port and are allocated in the first accessible day.

Table 21: Operational decision inputs

Input Name	Type	Value Range	Unit
Inter-transit time	Operational	10	min
Time to start working	Operational	20	min
Maximum visit for a CTV	Operational	4	$-$
Regular number of technicians	Operational	2	$-$
Maximum number of technicians	Operational	4	$-$
Preventive maintenance	Operational	57.5	$h/year$
Minimum working limit	Operational	2	h
Shift start	Operational	8:00	$hh:mm$

5.2.5 Vessel chartering

Figure 59 shows the simulation phase, which is explained in the section. In order to demonstrate a clear framework, the box associated with this section is highlighted and other boxes are made transparent.

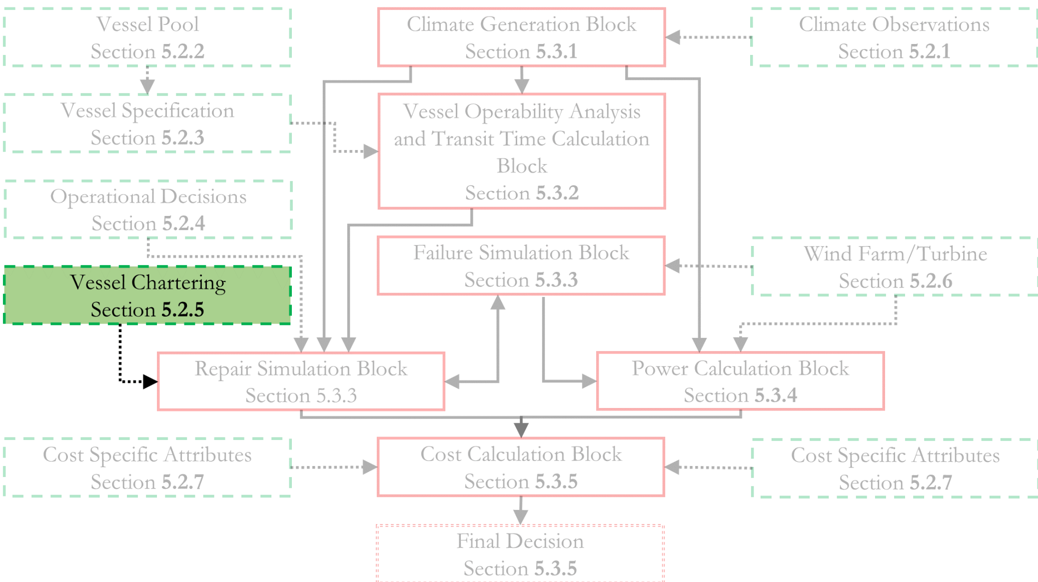

Figure 59: Definition of simulation phase

5.2.5.1 CTV chartering

It is envisaged that CTVs are under continuous charter within the simulation period (5 years). However, the charter payment is increased by the defined inflation rate at the end of each simulation year. Bareboat charter is defined as the most suitable charter agreement type, since the operators can control every aspect such as fuel and technician as their specific requirements. The CTV charter rates in Table 22 are adopted from Dalgic *et al.* (2015a). Due to better capabilities, 26 m WFSV has a higher daily charter rate, in which only vessel cost is taken into account. In a similar manner, the daily charter rates reduce in accordance with the vessel capability.

Table 22: CTV charter rates

Input Name		Value		Unit
Vessel name	26 m WFSV	21 m WFSV	17 m WFSV	
Charter rate	3500	2600	1750	$£/day$

5.2.5.2 Jack-up vessel chartering

- Commercial vessel charter rates

It is envisaged that jack-up vessel can be chartered in two different ways: short term and long term. However, there is limited information in the offshore wind market and it is strictly confidential. Therefore, in order to define the jack-up vessel charter rates, the daily rates of the commercial vessels are utilised. Although the offshore wind vessel market does not explicitly operate in the same way as the shipping vessel market, bulk carriers and tankers are utilised due to their Capital Expenditure (CAPEX) similarity as well as their charter rates presenting a representative trend over specified chartering scenarios.

CAPEX, which is the capital invested by a company to acquire or upgrade fixed, physical, non-consumable assets, is proportional to the capabilities of the vessel. When the influence of the economic variations associated with the new building market is neglected, vessels with higher speed, better lifting capability (hook height, lifting tonnage, etc.), deeper operability and longer durability in harsher conditions have higher CAPEX values. With regards to charter rates, it is also anticipated that the vessels with better structural condition and with the ability to perform the O&M activities more efficiently, have higher charter cost. Therefore, the relationship between the CAPEX of different vessels and associated charter rates for different periods is utilised to establish the estimation of the rates for the jack-up vessels.

In this context, Figure 60 and Figure 61 show the spot market charter rates for Capesize, Panamax, Handymax type bulk carriers and Very Large Crude Carrier (VLCC), Suezmax, Aframax, and Product type tankers. In addition, Figure 62 and Figure 63 demonstrate time charter (1 year) rates for the same vessel types. Astrup Fearnley (2014) provides the charter rates for all these vessel types in weekly intervals. Although bulk carrier charter rates are published as daily rate ($/day), tanker charter rates are published in Worldscale (WS) system, which provides a method of calculating the freight applicable to transporting oil by reference to a Standard Vessel on a round trip voyage from one or several load ports to one or several discharge ports. The definition of Standard Vessel is 75,000 tons total capacity vessel performing a round voyage and expressed in dollars per ton of cargo (Worldscale, 2015). A 75,000 ton vessel is 'average' type of vessel, in terms of size, number and performance; and therefore, the Worldscale rate for this vessel is always given as WS100. For instance, WS150 means 150 per cent of the WS100 rate and WS 50 mean 50 per cent of the WS100 rate. At this stage, WS100 rates are obtained from the Worldscale Association. Although, charter rates are provided in weekly intervals, the annual mean WS100 rates are provided by the Worldscale Association. By synthesising all the information above, the conversion from WS rate to daily rate is applied by the equation below;

$$Daily\,rate = \big((WS100\ x\ WS\ Index\ x\ DWT) - (Fuel\ +\ Port\ Costs +\ Dues)\big)\ /Round\ Trip\ Days \qquad \text{Equation 78}$$

In general context, the charter rates vary within the defined period (2004-2010); the spot market charter rates are higher than the time charter rates and larger vessels have higher charter rates than the smaller vessels in the same category (bulk carrier and tanker categories). In order to be consistent within the values, the charter rates are converted to British Sterling with the exchange rates provided by FXTOP (2015) (Figure 64). Astrup Fearnley (2014) also provides the CAPEX values of the associated vessels within the same period. The CAPEX values are provided in dollars; therefore, they are also converted to British Sterling with the exchange rates provided by FXTOP (2015). By considering the daily charter rates and the CAPEX values, the proportion of the CAPEX to the charter rates is calculated and presented in Figure 65-Figure 68. The 'CAPEX/Charter rate' values present different behaviour depending on the vessel type, size, year, and charter type; therefore, one of these vessels has to be selected for the estimation of jack-up vessel charter rates. In this context, test and trials are performed, which are explained in the following section.

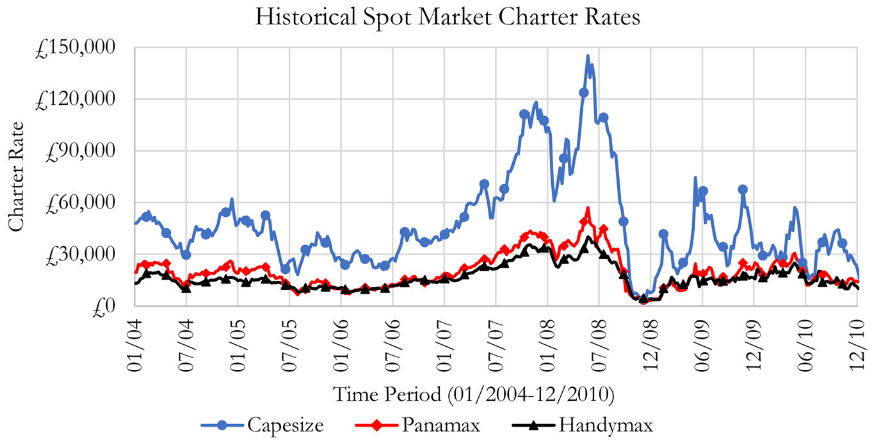

Figure 60: Bulk carrier historical daily charter rates (spot market)

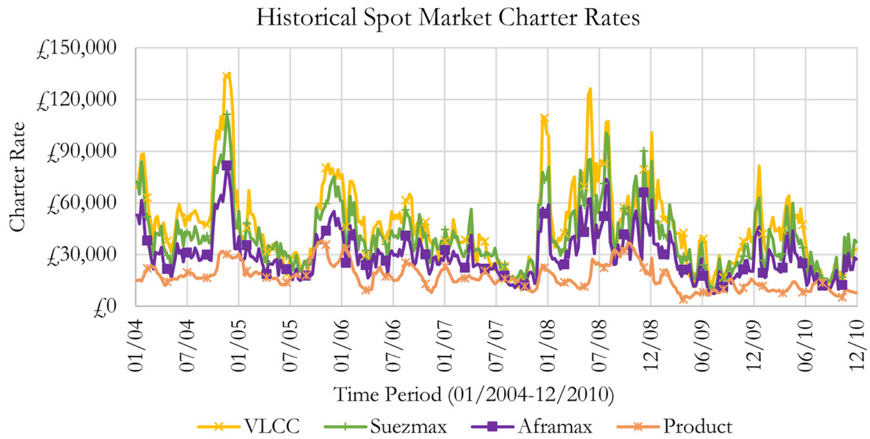

Figure 61: Tanker historical daily charter rates (spot market)

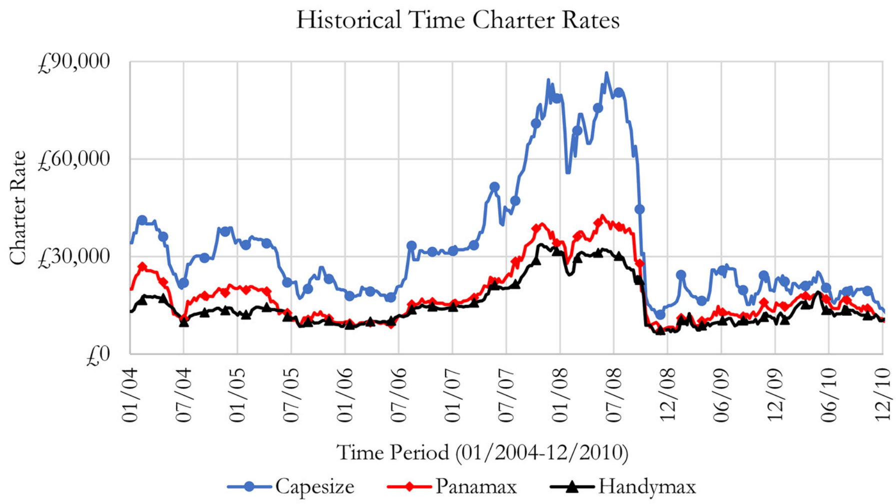

Figure 62: Bulk carrier historical daily charter rates (time charter)

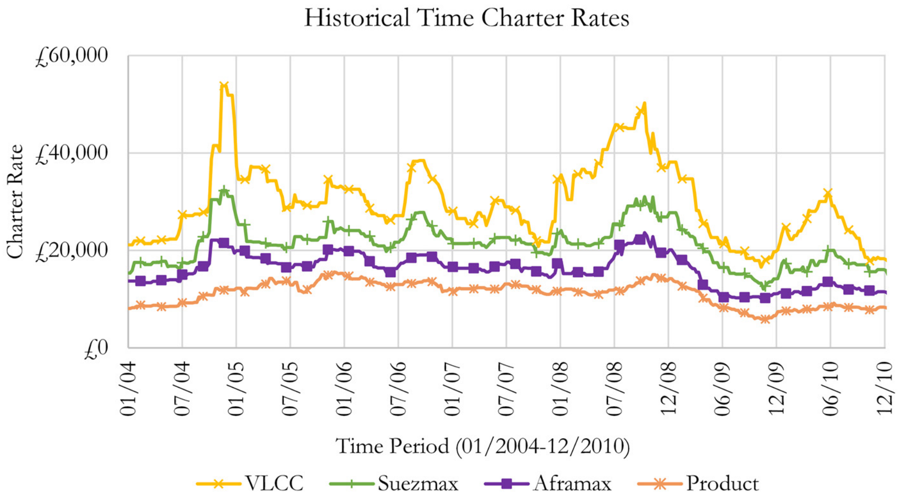

Figure 63: Tanker historical daily charter rates (time charter)

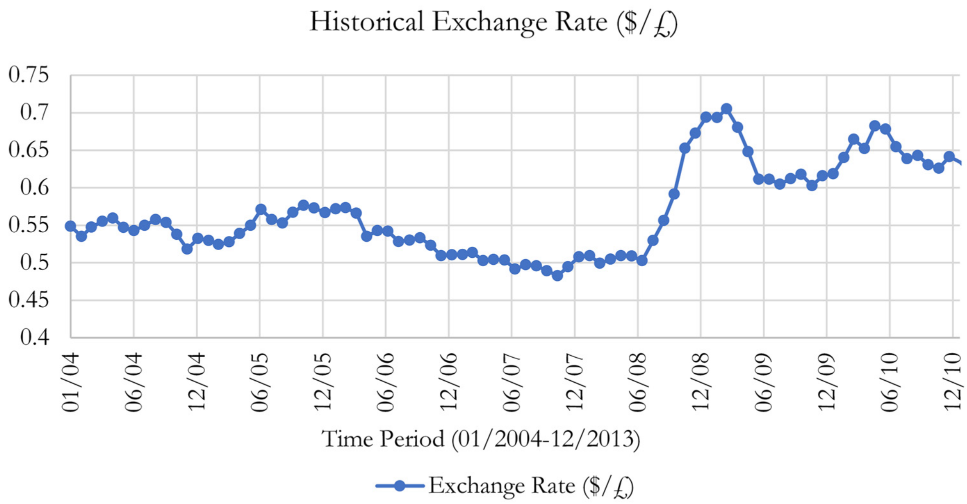

Figure 64: Historical $/£ exchange rates

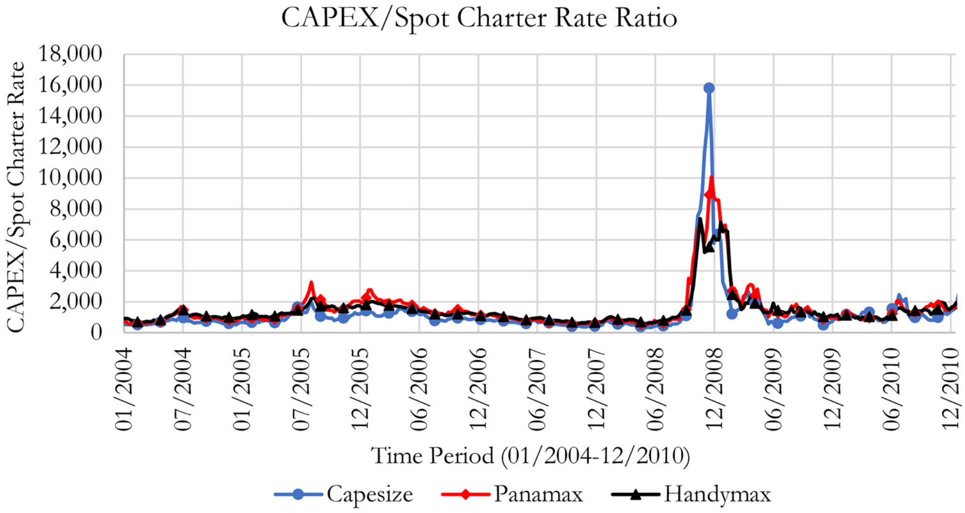

Figure 65: Bulk carrier 'CAPEX/Spot charter rate' ratios

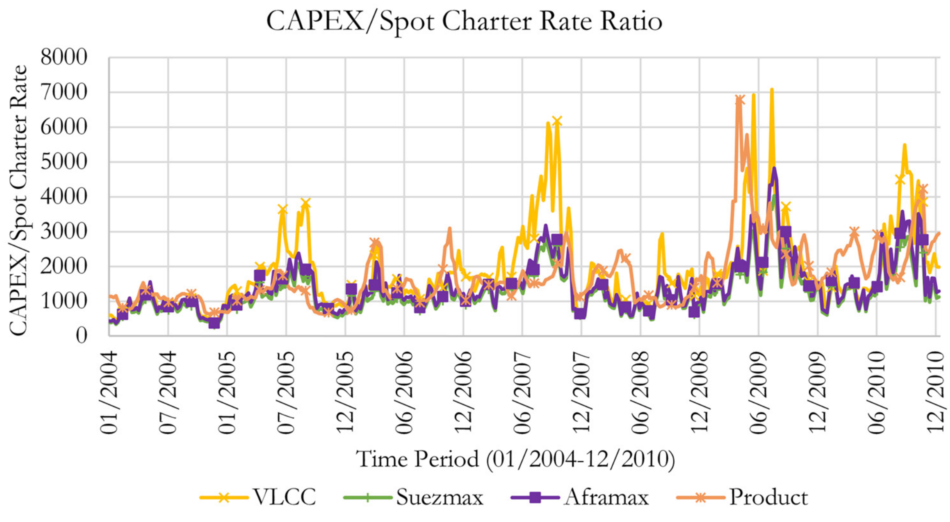

Figure 66: Tanker 'CAPEX/Spot charter rate' ratios

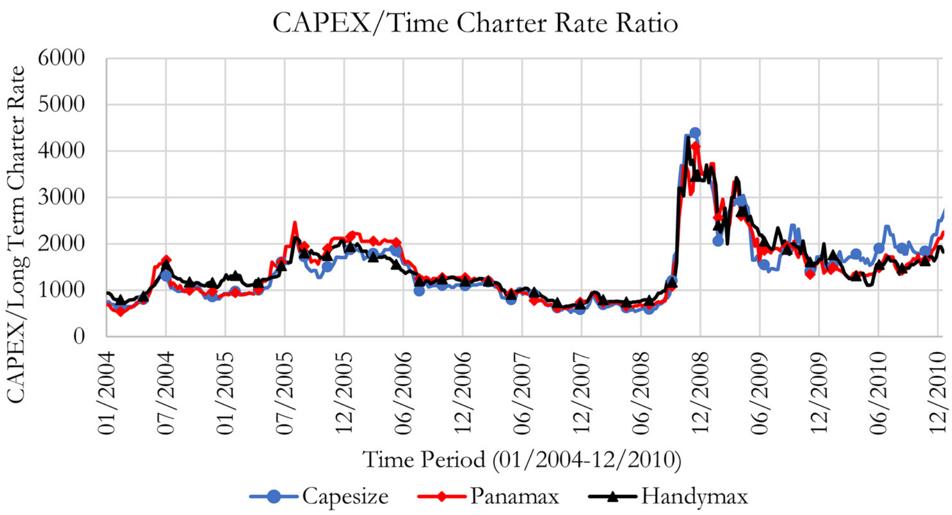

Figure 67: Bulk carrier 'CAPEX/Time charter rate' ratios

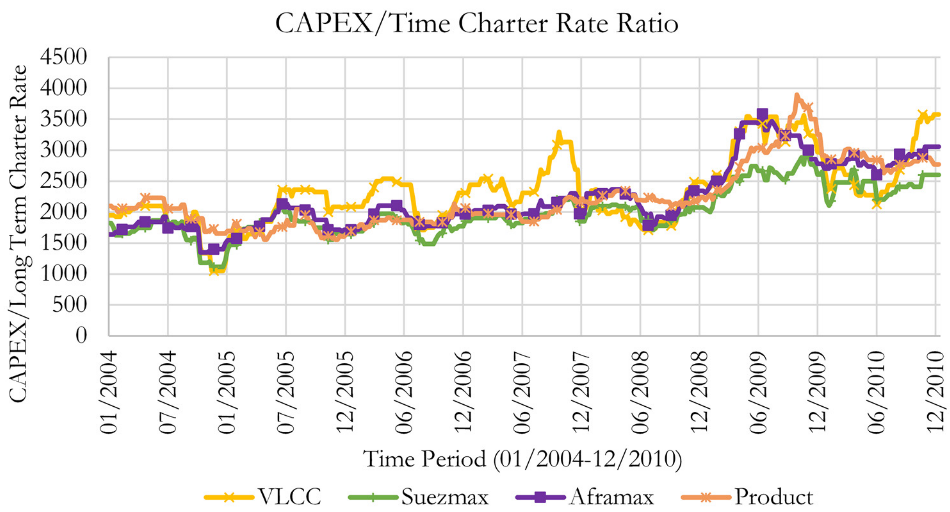

Figure 68: Tanker 'CAPEX/Time charter rate' ratios

- Distribution fitting

In this section, the 'CAPEX/Charter rate' values are fitted to major distributions. Figure 69 is a sample demonstration for the distribution fitting. In this sample, 'CAPEX/Spot market rate' values are fitted to distributions and the quality of the fits are ranked depending on the AICc scores as shown in Table 23. The distribution parameters are also provided in Table 23. The name and description of the parameters can be found in Table 47. By utilising the distribution parameters, same distributions can be generated without using the actual observations.

The light blue vertical bars in Figure 69 denote the actual 'CAPEX/Charter rate' values. The majority of the sample population is grouped between '400' and '2000'; the values above '2000' are rarely observed. From the point of AICc scores, the key aspect is the relativity of the scores. The distribution with the lowest AICc score best represents the empirical values among all the distribution family. In this case, it is identified that generalised extreme value distribution provides the best fit for the 'CAPEX/Spot market rate' values. The dashed thick blue line shows the best fit among all the distribution family. This procedure is repeated for each vessel type and each charter period in order to define the best jack-up vessel rate representation. For presentation purposes and improve the reading quality of the thesis, the remaining distribution fits are presented in Appendix A Figure 183-Figure 195. In addition, the remaining distribution parameters are provided in Appendix A Table 48-Table 60.

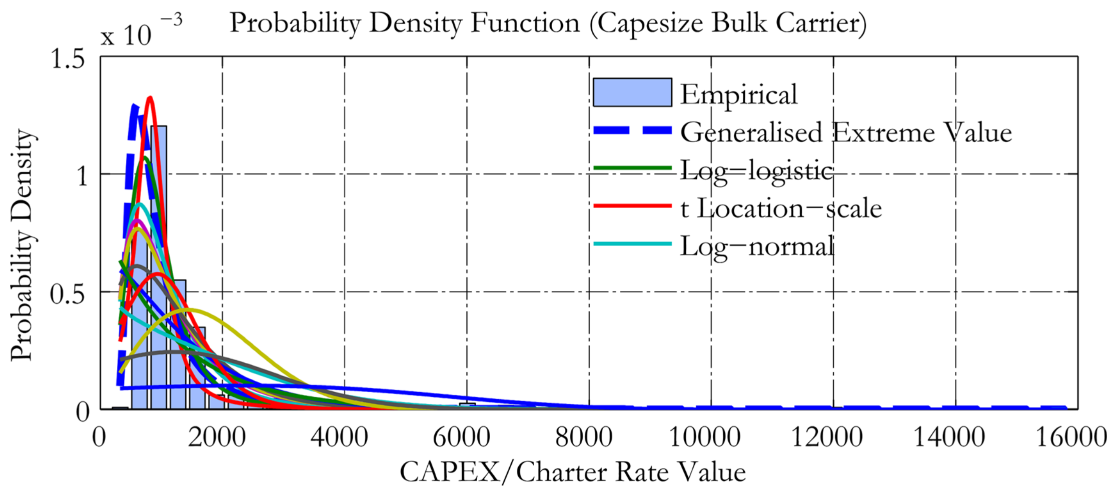

Figure 69: Capesize bulk carrier 'CAPEX/Spot market charter rate' distributions

Table 23: Capesize bulk carrier 'CAPEX/Spot charter rate' distribution rankings

Distribution name	AICC	Parameter		
Generalised extreme value	5517.51	0.44	309.16	710.24
Log-logistic	5559.48	6.76	0.30	-
t Location-Scale	5620.82	811.81	256.10	1.47
Log-normal	5626.13	6.82	0.60	-
Inverse Gaussian	5654.52	1205.57	2384.37	-
Birnbaum-Saunders	5684.97	990.96	0.67	-
Gamma	5815.20	1.98	610.34	-
Weibull	5878.71	1289.50	1.16	-
Exponential	5894.96	1205.57	-	-
Logistic	6011.38	937.60	434.59	-
Nakagami	6064.71	0.41	4106996.85	-
Rayleigh	6346.06	1433.00	-	-
Rician	6348.08	47.93	1432.70	-
Normal	6421.10	1205.57	1631.23	-
Extreme value	6921.27	2324.87	3610.93	-

After identifying the distributions that best represent the calculated 'CAPEX/Charter rate' values in Figure 65-Figure 68, demonstrative charter rates are generated for conceptual jack-up vessels. These conceptual jack-up vessels, which are envisaged to present the lowest (£75m) and the highest (£200m) boundaries of the offshore wind market, have £75m, £100m, £125m, £150m, £175m, and £200m CAPEX. In this respect, £75m jack-up vessels is expected to be the least capable vessel, conversely £200m jack-up vessel is expected to be the highest capable, new generation vessel. Although, there is no certain value, the jack-up charter rates are expected to be in the range of £50,000 and £150,000 (Dalgic *et al.*, 2014, The Crown Estate, 2014). However, it should be highlighted that these estimations can vary depending on the vessel size, capability, availability, and market supply/demand balance. Therefore, the jack-up vessel charter rates are not defined as a constant value in the case study; instead, these rates are randomly selected from the identified distributions, which provides probability to have higher or lower charter rates within the simulations as they can be observed in the market.

When all the demonstrative charter rates are investigated, it can be seen that there is a probability that the jack-up charter rate can be estimated as '£0' for short term as seen in Figure 196-Figure 198, if one of the Capesize, Panamax or Handymax bulk carrier 'CAPEX/Charter rate' distributions are utilised. Therefore, these vessel types are not considered for the jack-up vessel charter rate estimation. The rates based on tanker types show better approximation; however, the long term demonstrative charter rates for VLCC, Aframax, and Product tankers appear to be lower than anticipated (Figure 205-

Figure 207). Considering both long term and short term demonstrative charter rates, Suezmax tanker is identified as the vessel that represents the jack-up vessel charter rates in a better way compared to other commercial vessel types (Figure 70-Figure 71). In this context, Figure 70 shows the distributions of the short term charter rates for the jack-up vessels. Similarly, Figure 71 shows the distributions of the long term charter rates for the same six jack-up vessels. All the other demonstrative charter rates can be found in Figure 196-Figure 207. As in commercial vessels, the short term charter rates are higher than the long term charter rates for the same vessel. The probability of having a certain jack-up charter rate is defined by the distributions in Figure 70-Figure 71. For instance, the short term charter rate of the jack-up vessel with £75m CAPEX value is expected to be between £31,000 and £145,000 with 95% probability. £65,000 is the value that has the highest probability to be selected from this particular distribution.

In addition to the long term and short term charter rate distributions, seasonal charter rates are also generated by the same distribution fitting approach. In this respect, the jack-up vessel charter rates are modelled separately for summer and winter, which are defined by the month that the chartered jack-up vessel arrives at the site. Summer denotes the period between April and September, inclusive; winter denotes the period between October and March, inclusive. In this case, the short term Suezmax 'CAPEX/Charter rate' values are split into two groups, one of which comprises of the highest 'CAPEX/Charter rate' values and the other group comprises of the lowest 'CAPEX/Charter rate' values. Figure 72 and Figure 73 illustrate the demonstrative seasonal charter rates for the jack-up vessels. Due to higher accessibility and lower power productivity, the jack-up vessel charter rates during summer are expected to be higher than the charter rates during winter. It is believed that considering high charter rates for summer and relatively low charter rates for winter is a reasonable representation of the current offshore wind industry.

The accuracy of the demonstrative jack-up vessel charter rates are confirmed by the offshore wind O&M experts. Due to the fact that there is no particular research in the field of jack-up vessel charter rates, it has not been possible to directly compare the market values and the generated values. The observations and expectations of the wind industry experts are within the range of demonstrated jack-up vessel charter rates. The jack-up vessel charter rates demonstrated in this section are also presented in Dalgic *et al.* (2015b) and Dalgic *et al.* (2013).

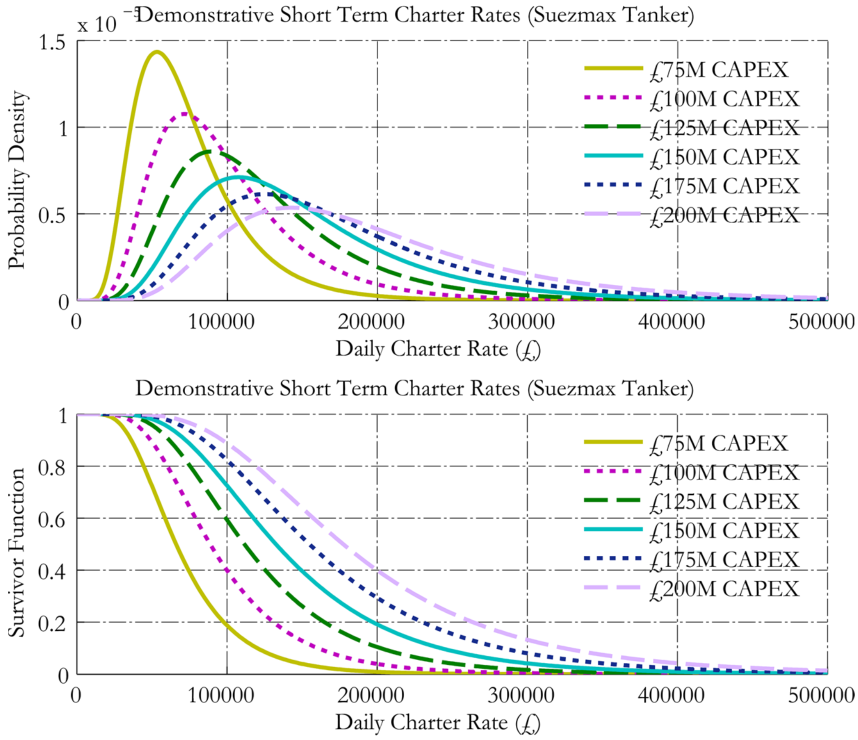

Figure 70: Demonstrative short term charter rates based on Suezmax tanker

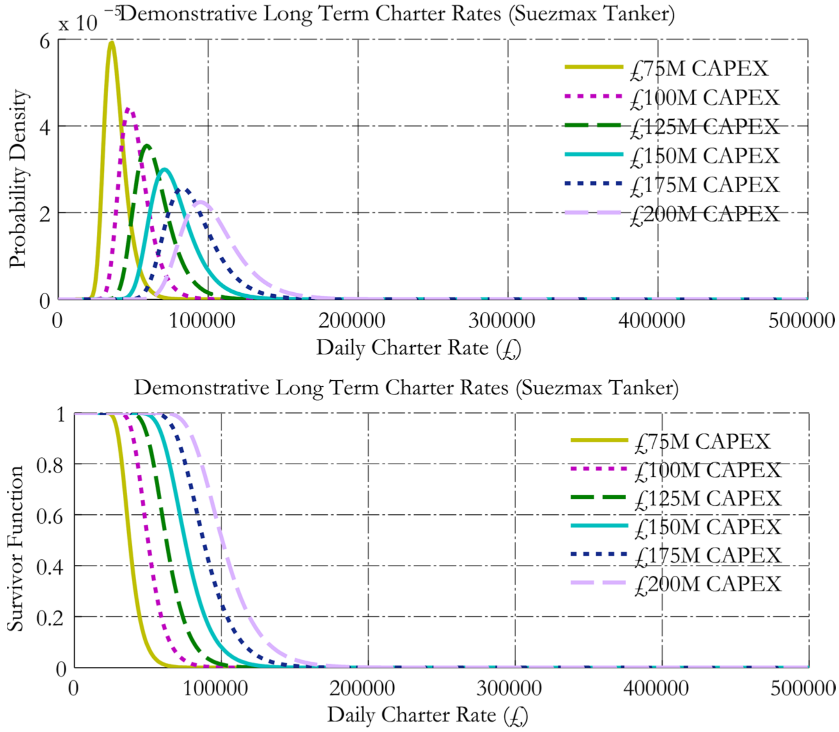

Figure 71: Demonstrative long term charter rates based on Suezmax tanker

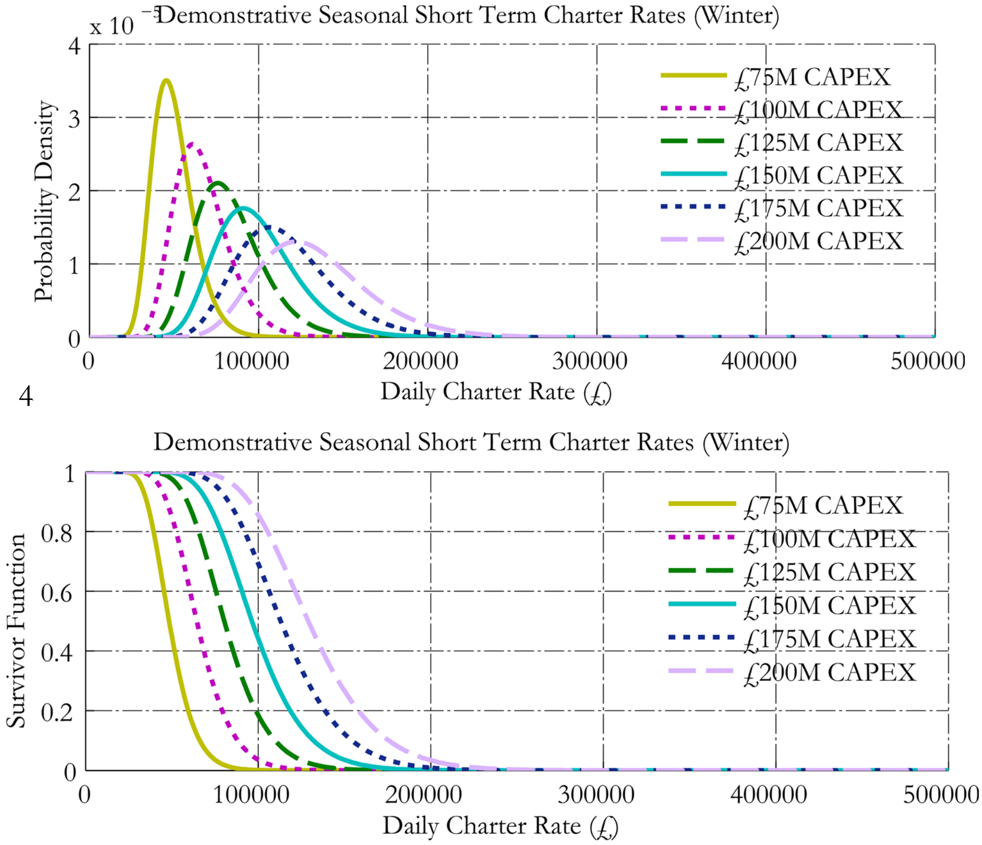

Figure 72: Demonstrative short term charter rates (winter) based on Suezmax tanker

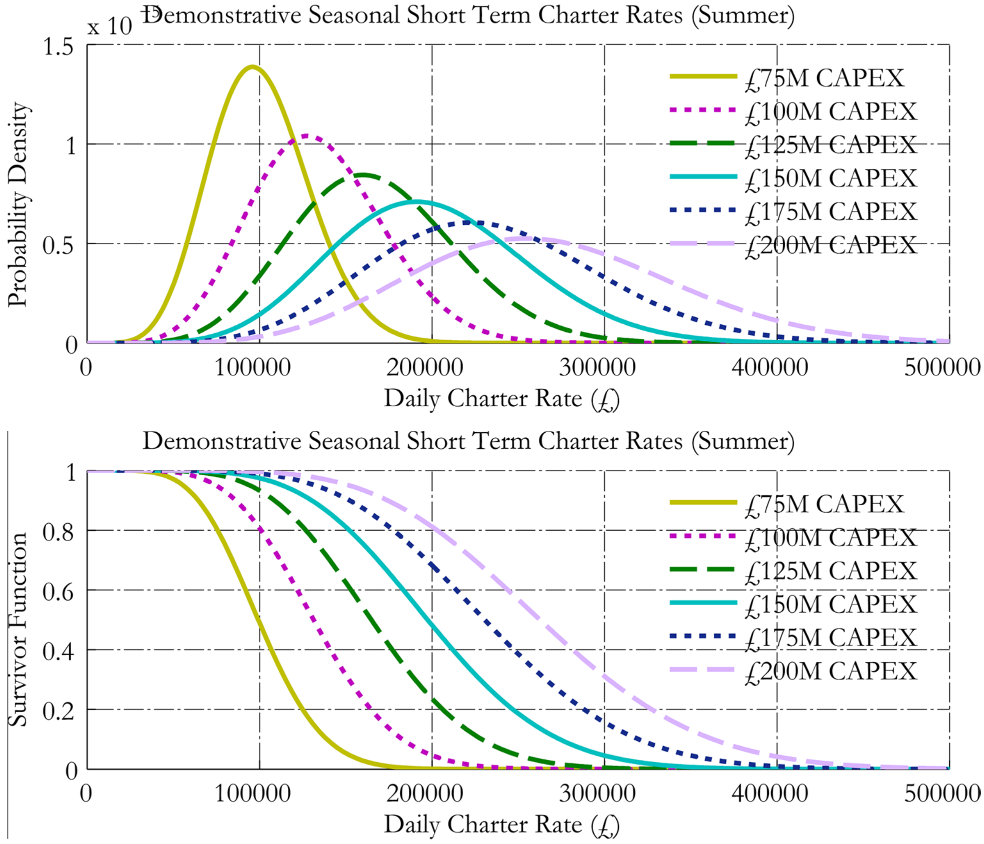

Figure 73: Demonstrative short term charter rates (summer) based on Suezmax tanker

- Demurrage rate calculation

The historical demurrage rates for different size of vessels are provided by Worldscale (2015). The annual average demurrage rates are presented in Table 24. Suezmax tankers are typically 160,000 dead weight tonnes (DWT). The proportion of the Suezmax tanker demurrage rates (labelled by red in Table 24) to the annual average spot market charter rates fits in a range of [0.48, 1.55]. In the simulations, a random number is generated within the [0.48, 1.55] range and multiplied by the daily charter rate to define the demurrage rate. The calculated demurrage rate is then added to the actual charter rate in order to calculate the penalty, which is going to be paid, if the jack-up vessel continues operating after initially agreed charter period is completed. For instance, if the charter rate is £100,000, and if the proportion of the demurrage is 0.5, the operator pays £100,000+£50,000 for each day that the jack-up vessel stays in the offshore wind farm after agreed charter period. In this case, the demurrage rates can be excessive due to the fact that vessel operator/owner can be tied up by a subsequent charter agreement (with another operator) and may need to pay fine by not meeting the requirements of the subsequent agreement.

Table 24: Historical demurrage rates

DWT $*10^3$	2004	2005	2006	Year 2007 Rate (£)	2008	2009	2010
80/89.9	8,733	8,791	9,227	9,117	9,874	14,057	11,968
90/99.9	9,661	9,725	10,177	10,116	11,061	15,974	13,585
100/109.9	10,589	10,715	11,263	11,240	12,276	17,891	14,879
110/109.9	11,517	11,649	12,213	12,489	13,625	20,128	16,658
120/129.9	12,445	12,583	13,298	13,613	14,974	22,364	18,114
130/139.9	13,536	13,737	14,655	14,987	16,458	24,281	20,055
140/149.9	14,601	14,836	15,877	16,236	17,807	26,518	21,510
150/174.9	16,511	16,759	17,912	18,484	20,235	30,032	24,583
175/199.9	18,967	19,369	20,626	21,356	23,472	35,144	28,465
200/224.9	21,424	21,842	23,612	24,478	26,845	40,256	32,347
225/249.9	24,016	24,589	26,597	27,476	30,083	44,729	36,875
250/274.9	26,473	27,062	29,311	30,473	33,320	49,841	41,242
275/299.9	29,066	29,809	32,161	33,471	36,693	54,953	44,315
300/324.9	31,931	32,694	35,147	36,468	40,200	60,065	48,520
325/349.9	34,660	35,441	37,996	39,466	43,438	65,816	52,725
350/399.9	38,618	39,425	42,339	43,962	48,564	73,484	58,871
400/449.9	43,667	44,783	48,310	49,956	55,039	83,069	66,635
450/499.9	49,398	50,552	54,281	56,451	62,054	95,210	75,692

5.2.6 Wind farm/turbine specific attributes

Figure 74 shows the simulation phase, which is explained in the section. In order to demonstrate a clear framework, the box associated with this section is highlighted and other boxes are made transparent. In order to present the operational environment in an actual way, an operating UK Round 2 offshore wind project is identified and considered in the operational simulations. The offshore wind farm is 40 nautical miles from the permanent operational base. Water depth varies between 24 m and 34 m. The site consists of 140 3.6 MW vertical axis turbines. A representative power curve for 3.6 MW turbines is presented and considered in the power calculations (Figure 75).

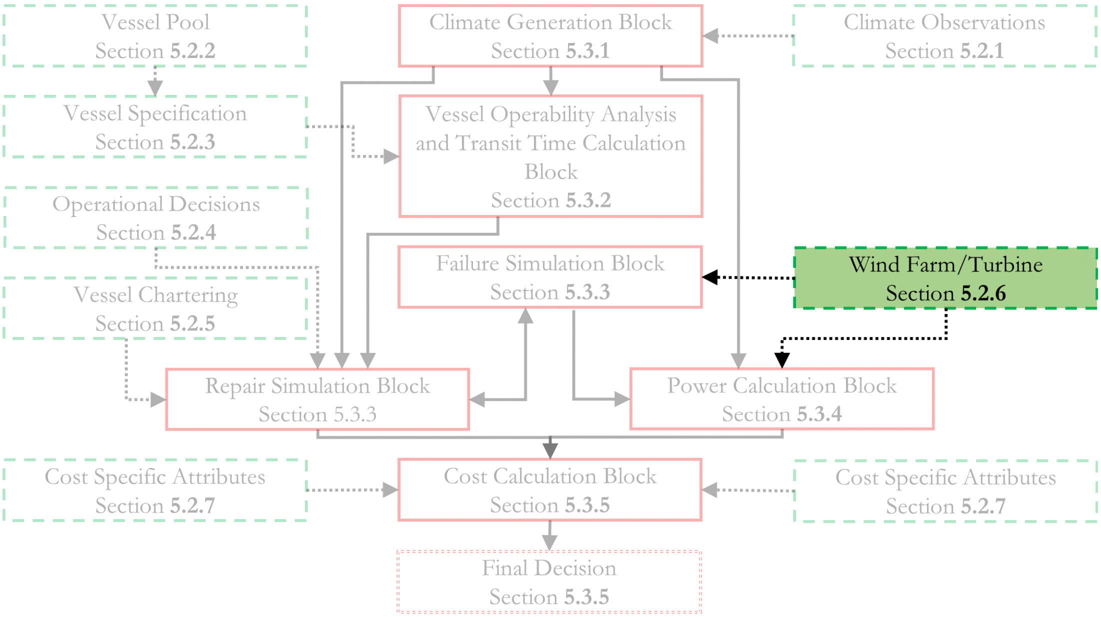

Figure 74: Definition of simulation phase

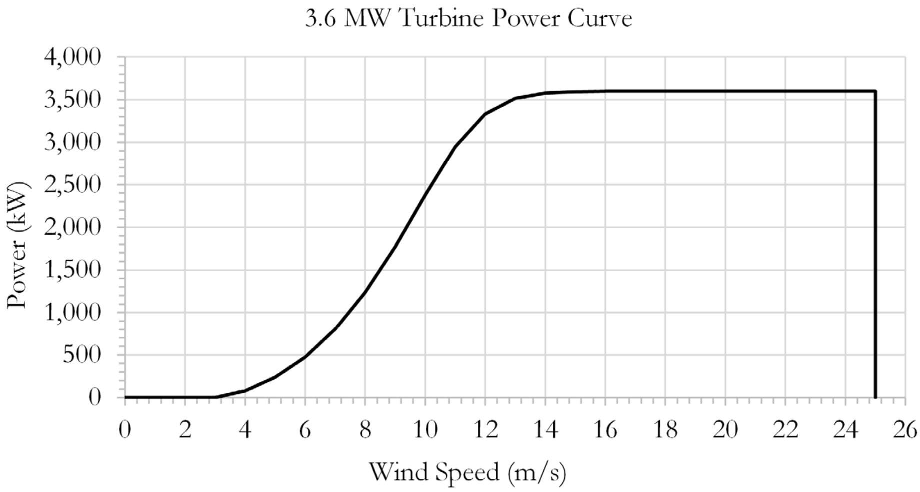

Figure 75: 3.6 MW turbine power curve

It is envisaged that a single turbine consists of 12 different components. These 12 components are associated with 12 minor failures and 4 major failures as in Table 25. In order to demonstrate the development and change of failure rates throughout the simulation period (5 years), all the constant failure rates, which are presented by Lindqvist and Lundin (2010), are modified to time dependent failure rates that are denoted by 2 parameters (shape k, scale λ) Weibull distributions (Table 26). In this case, the mean values of the Weibull failure rate distributions are equal to the constant failure rates provided by Lindqvist and Lundin (2010).

The bathtub curves are generated by plotting the rate of early failures when first introduced, the rate of random failures with constant failure rate during the components useful life, and finally the rate of wear-out failures as the product exceeds its design lifetime. The component and system failure rate distributions, which are created by the Weibull parameters in Table 26 are graphically presented in Figure 76. Each colourful line denotes a failure type, since the probability of the major failures are lower than the minor failures, the 4 colourful lines at the bottom of Figure 76 denote the major failure types. Sensors do not deteriorate in time (Bagajewicz, 2001); therefore, their failure rate is not time dependent. The black line represents the total failure rate of the turbine system, assuming the turbine components create a series of turbine system, in which any component failure cause a system failure. At this stage, it is important to highlight that the knowledge and experience related to reliability figures and the failure rates of offshore wind turbine components are very limited, therefore, it should be possible to utilise more accurate offshore wind failure rates in the future. Table 27 shows the additional wind farm inputs required for the simulations. In this case study, all the components are assumed to be brand new. Considering the initial failure rate distributions in Figure 76, around 10 failures are expected at the beginning of the commissioning of the wind farm. Within the wear-in stage, the failure rates gradually decrease; therefore, the number of failures is expected to decrease. In the wear-out stage, the component and entire turbine failure rates start to increase due to fatigue.

Table 25: Turbine components and failure types

No	Component	Failure type	Access Type	Repair Time (days)
1	Electrical system	Minor	CTV	0.17
2	Electronic control	Minor	CTV	0.15
3	Sensors	Minor	CTV	0.16
4	Hydraulic System	Minor	CTV	0.18
5	Yaw System	Minor	CTV	0.16
6	Rotor Hub	Minor	CTV	0.18
7	Mechanical Brake	Minor	CTV	0.16
8	Rotor Blades	Minor	CTV	0.18
9	Gearbox	Minor	CTV	0.17
10	Generator	Minor	CTV	0.15
11	Support & Housing	Minor	CTV	0.14
12	Drive Train	Minor	CTV	0.17
13	Blade	Major	Jack-up	1
14	Gearbox	Major	Jack-up	6
15	Generator	Major	Jack-up	3
16	Transformer	Major	Jack-up	6

Table 26: Weibull distribution parameters

No	Infant λ	Infant k	Random λ	Random k	Wear λ	Wear k
1	0.2	0.7	6	1	13	5
2	0.37	0.75	10	1	13	4
3	0.37	0	1.25	1	13	0
4	0.4	0.43	5	1	13	4
5	0.9	0.41	4	1	16	4
6	0.9	0.41	4.8	1	16	4
7	0.5	0.29	4.8	1	16	4
8	0.5	0.29	8	1	16	4
9	0.7	0.2	20	1	15	3.5
10	0.8	0.3	20	1	16.5	5
11	0.8	0.5	30	1	19.8	12
12	0.3	0.15	50	1	20	11
13	1	0.0015	280	1	30	10
14	1	0.05	30	1	24	14
15	1	0.015	25	1	24	15
16	1	0.013	100	1	24	19

Table 27: Wind farm/turbine inputs

Input Name	Type	Value Range	Unit
Hub height	Power	77.5	m
Number of components	Structure	12	$-$
Cut in speed	Power	3	m/s
Cut out speed	Power	25	m/s
Number of turbines	Power- Operation- Failure	140	$-$
Age of components	Operation- Failure	0 (all new)	$year$

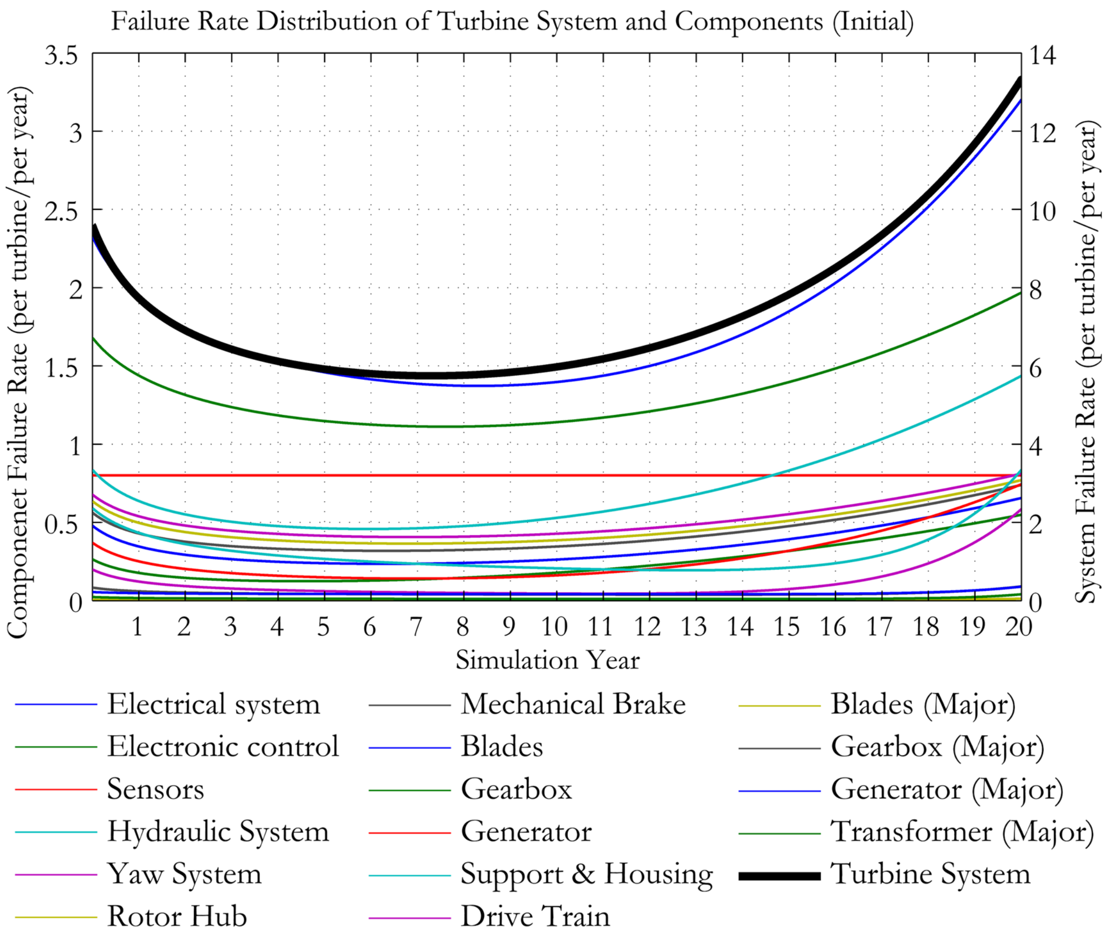

Figure 76: Failure rate distributions (Initial)

5.2.7 Cost specific attributes

Figure 77 shows the simulation phase, which is explained in the section. In order to demonstrate a clear framework, the box associated with this section is highlighted and other boxes are made transparent. Table 28 shows the costs considered in the simulations. Although, the majority of these aspects are self-explanatory; a detailed explanation is required to clarify how these aspects are modelled within the simulation logic. Due to the fact there is no certain value for the jack-up vessel mobilisation in terms of required time and cost, these aspects are defined by a discrete distribution, for which the probabilities are also presented in this table. Considering the fact that shorter lead time is generally associated with a higher cost, the mobilisation costs are assumed to be inverse proportional to the time required. Between three and six months is a typical period for a jack-up vessel mobilisation; however, longer waiting times can be expected in some circumstances (The Crown Estate, 2014). Therefore, it is assumed that the jack-up vessel can be made available on the site by 60% probability. The remaining 40% is shared by the shorter (1-2 months) and longer (7-8-9-10 months) periods. When the jack-up vessel charter agreement is signed, the operator has to wait for a certain period of time, which is defined randomly among the values in Table 28.

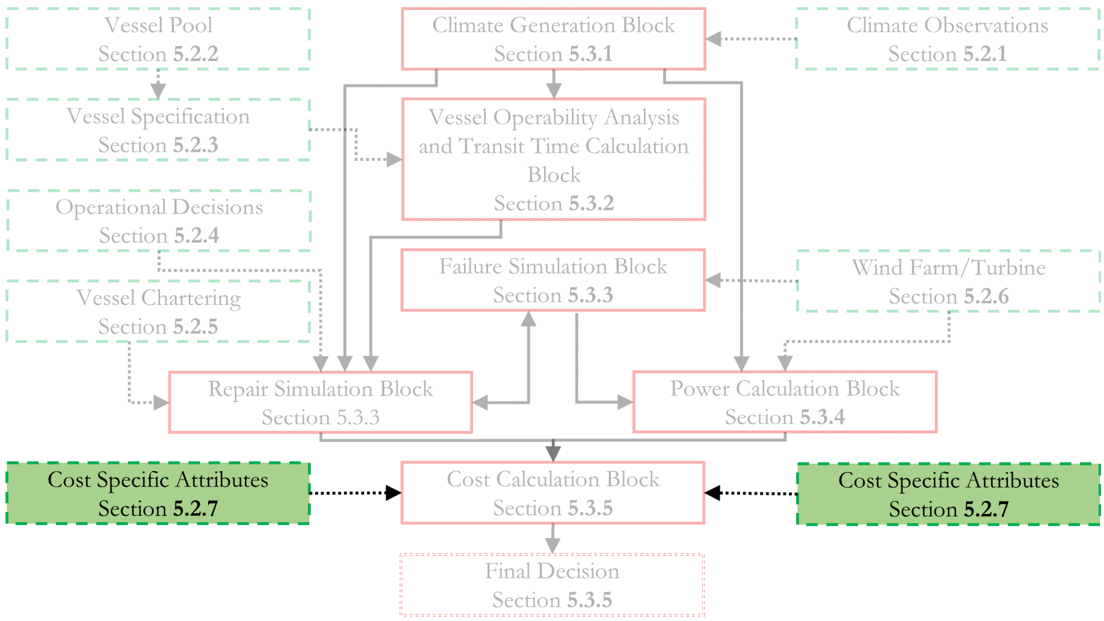

Figure 77: Definition of simulation phase

The jack-up vessel charter costs are defined by the distributions identified in the previous section (Section 5.2.6); the initial input for these distributions is £73.11M CAPEX. The crew and technician costs presented in Table 28 are the average values; since, there is a salary range in a vessel, which varies with respect to the rank and experience of the crew member. The values in the brackets show the number of crew/technicians associated with each category; therefore, these cost aspects are multiplied by the values in the brackets in order to calculate the total costs. The CTV fixed cost and the CTV O&M technician cost is directly proportional to the number of CTV in the O&M fleet; therefore, the total costs associated with these aspects are variable.

The turbine component costs are adopted from Lindqvist and Lundin (2010). A cost value is associated with each failure mode defined in the previous section. Therefore, all the components have a minor failure cost, and four of these components also have a major failure cost. These failure costs are only related to the supply of the component. The operations (transportation, installation, etc.) are considered within the other cost aspects. It is assumed that turbine components are always available, therefore, supply chain issues are neglected in the thesis.

Table 28: Cost specific attributes

				Source
Electricity price (Offshore wind)	£140/MWh			(The Crown Estate, 2012)
Fuel cost	£550/ton			(Bunker Index, 2015)
Jack-up vessel mobilisation	Month	Cost	Prob.	
	1	£1M	0.05	(Kaiser and Snyder, 2010, Dalgic *et al.*, 2015b)
	2	£0.9M	0.05	
	3	£0.8M	0.10	
	4	£0.7M	0.25	
	5	£0.6M	0.25	
	6	£0.5M	0.10	
	7	£0.4M	0.05	
	8	£0.3M	0.05	
	9	£0.2M	0.05	
	10	£0.1M	0.05	
Jack-up vessel CAPEX	£73,110,000			Osborne (2004)
Jack-up vessel crew cost (annual average)	£37,000 (30)			
Jack-up vessel O&M technician cost (annual average)	£45,000 (12)			
Jack-up vessel management cost (annual average)	£43,000 (4)			
Jack-up vessel dry-dock cost	£1,000,000			(Dalgic *et al.*, 2015b)
Jack-up vessel fixed cost (provision, overhead, etc.) (annual average)	£200,000			
CTV technician cost (annual average)	£45,000			
CTV crew cost (annual average)	£53,500 (2)			
CTV fixed cost (port, provision, overhead, etc.) (annual average)	£50,000/CTV			
CTV charter cost	26 m WFSV	21 m WFSV	17 m WFSV	(Dalgic *et al.*, 2015a)
	£3,500	£2,600	£1,750	
	Minor	Major		
Electrical system	£555	N/A		(Lindqvist and Lundin, 2010)
Electronic control	£4,121	N/A		
Sensors	£1,200	N/A		
Hydraulic System	£1,276	N/A		
Yaw System	£551	N/A		
Rotor Hub	£4,288	N/A		
Mechanical Brake	£2,405	N/A		
Rotor Blades	£18,174	N/A		
Gearbox	£3,243	£75,000		
Generator	£11,189	£400,000		
Support & Housing	£11,189	£120,000		
Drive Train	£13,862	£42,000		

5.3 Analysis/Calculation sections

5.3.1 Climate generation block

Figure 78 shows the simulation phase, which is explained in the section. In order to demonstrate a clear framework, the box associated with this section is highlighted and other boxes are made transparent. In order to preserve the variability in performance driven by climate, unique artificial datasets are generated for each simulation. By using the described methodology, the key characteristics of mean, annual distribution, and access window duration periods are preserved. In addition, correlation between different climate parameters are preserved. In the case study, 1000 different climate datasets, which the number is defined by trial and error, are generated and characteristics of these datasets are compared with the original datasets. The required number of simulations can be defined by calculating the level of convergence. The basic approach is carry out multiple independent simulations and ensure these simulations reach approximately the same solution.

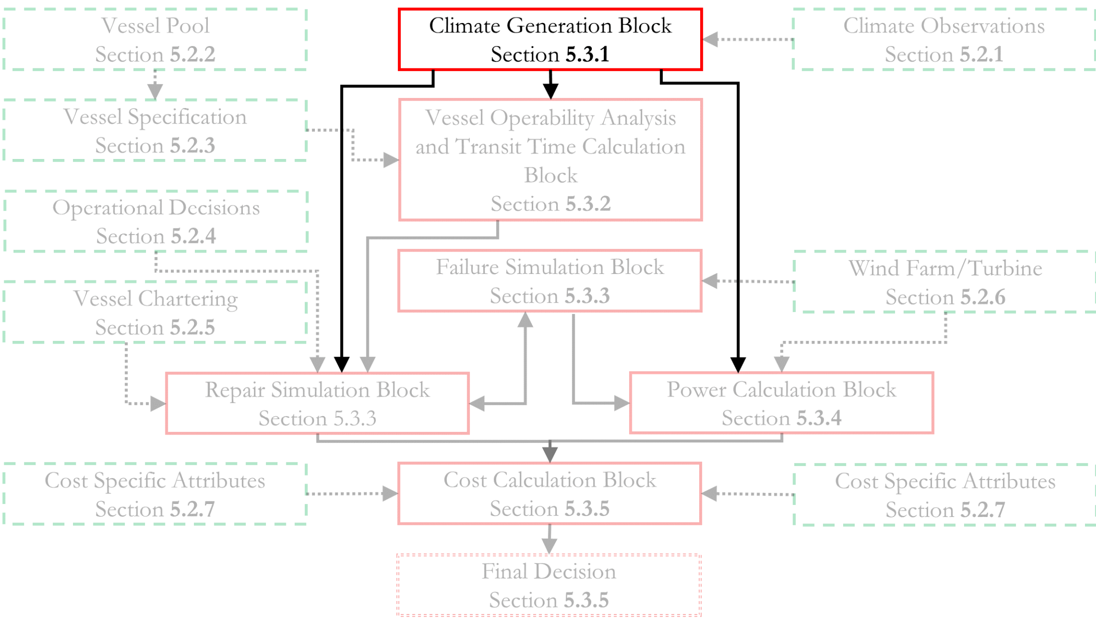

Figure 78: Definition of simulation phase

5.3.1.1 Defining the number of hidden layers, neurons, and the number of lags for the network

In many practical problems, one hidden layer in the network structure is sufficient for modelling any kind of multivariate function (Chui and Li, 1992, Li, 1996, Ismailov, 2014). Therefore, the number of hidden layers is set to '1'. At the second stage, the number of neurons in the hidden layer and the number of lags have to be defined. In this respect, trial and error method is utilised. Artificial datasets are generated by using several feedback delays and number of neurons in hidden layers, which vary from 1 to 75 with 1 step interval.

The results for wind speed dataset generation are presented in Figure 79-Figure 82. The wave height and wave period dataset generation results are presented in Figure 208-Figure 215 in Appendix A in order to improve the reading quality of the thesis. The graphs on the left hand side of these figures show the results relative to the increasing feedback delay and the graphs on the right hand side show the results relative to the increasing neurons in the hidden layer. The numbers under each profile denote the number of feedback delays (graphs on the left) and the number of neurons (graphs on the right). For each feedback delay profile, the number of neurons varies between 1 and 75; and represented by the lines starting from 3 o'clock direction continuing anticlockwise. Similarly, for each hidden layer size profile, the number of feedback delays varies between 1 and 75; and represented by the lines starting from 3 o'clock direction continuing anticlockwise.

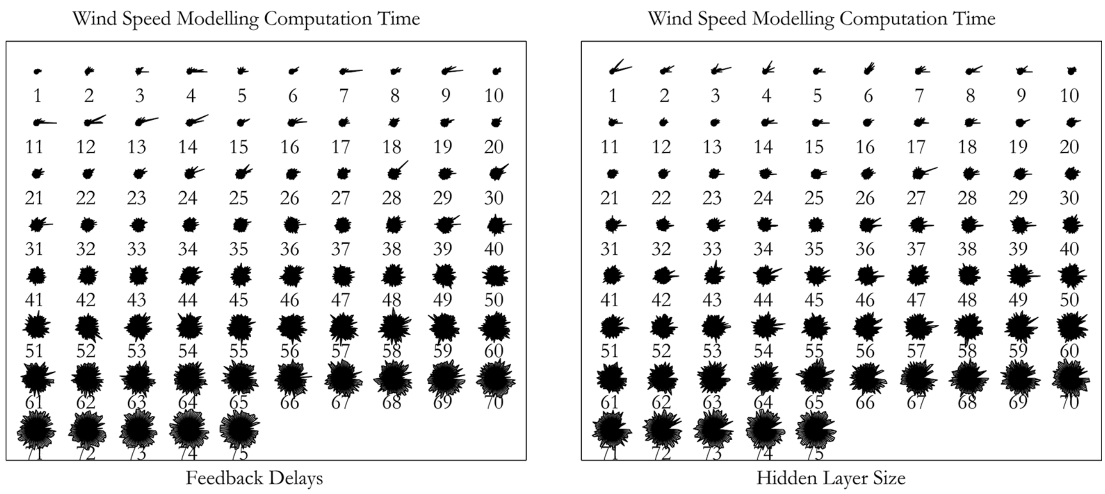

Figure 79: Wind speed model computation time diagram

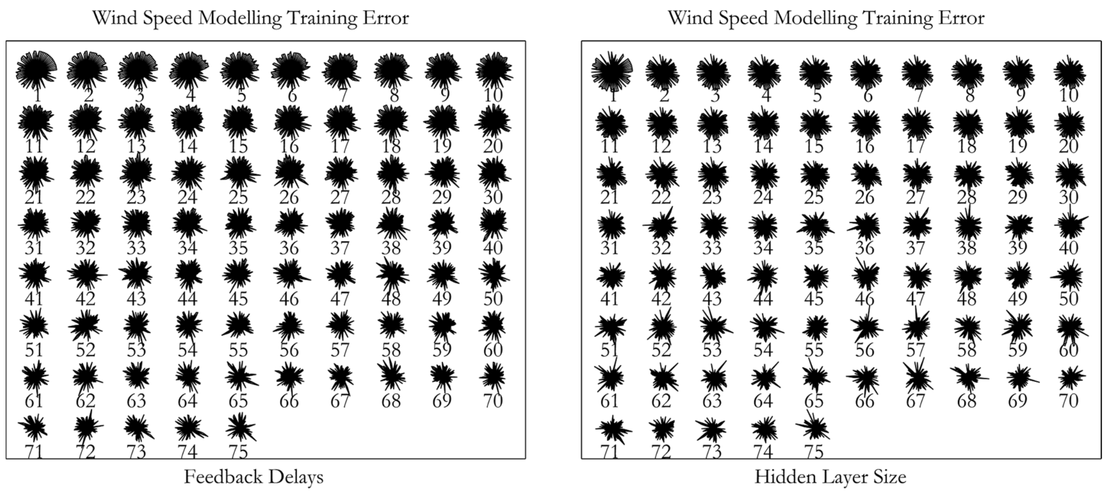

Figure 80: Wind speed model training error diagram

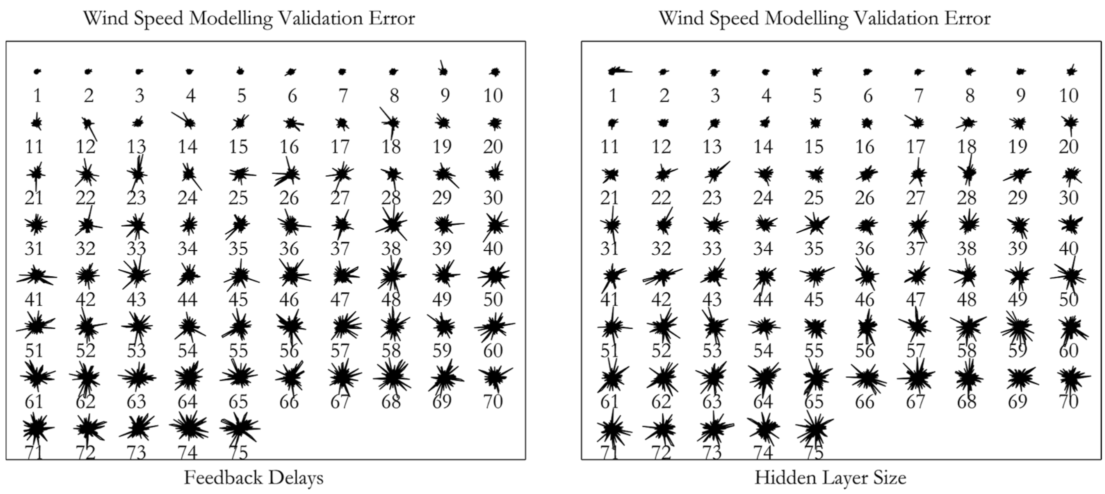

Figure 81: Wind speed model validation error diagram

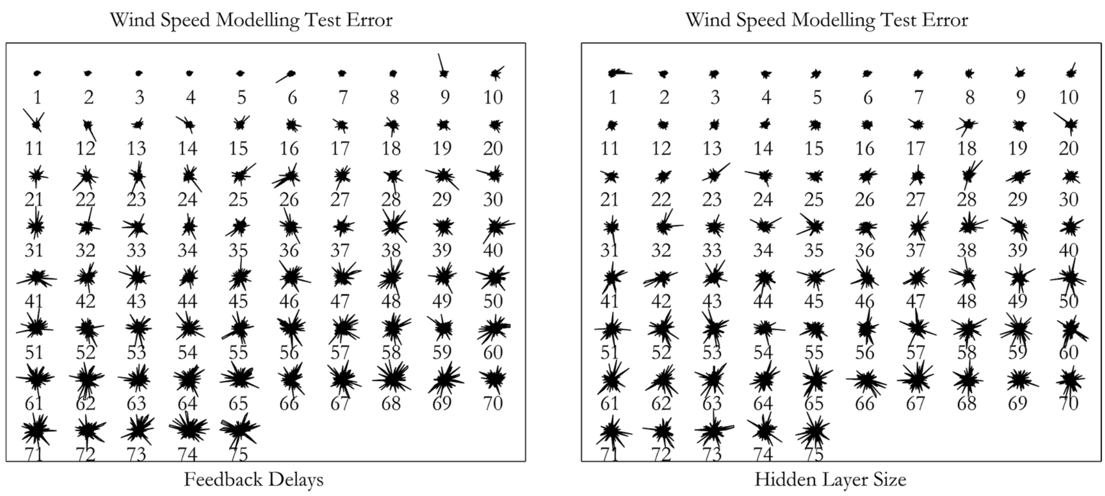

Figure 82: Wind speed model test error diagram

The computation times are shown in Figure 79 and it can clearly be seen that the computation time increases proportionally by the increase in the number of feedback delays and the number of neurons. This is because both circumstances increase the complexity of the network structure. 21.21 seconds and 2145.80 seconds (~36 minutes) are identified as the lowest and the highest computation times for a single wind speed dataset generation. Figure 80, Figure 81 and Figure 82 demonstrate the errors associated with training, validation, and test stages, respectively. The increase in the number of feedback delays and neurons decreases the error in the training stage; because, more complex networks better represent original dataset. However, if the network becomes highly complicated, it loses the flexibility to represent validation and testing datasets, in which the error increases by the increase in the number of feedback delays and the number of neurons.

The optimum number of lags and neurons can be identified by calculating the weighted average of the errors in each category. Since the first half of the original dataset is set for training, the third quarter and the fourth quarter are employed in validation and testing stages, the weights are set to 0.5, 0.25 and 0.25 for training, validation and test errors, respectively. Table 29 shows the number of lags and neurons for each dataset type (wind speed, wave height and wave period), which result in minimum error.

Table 29: Neural network properties

Input Name	Wind Speed	Wave Height	Wave Period
Number of lags	14	39	49
Number of neurons	3	41	3
Training error	0.9484	0.0170	0.0562
Validation error	1.0061	0.0705	0.0978
Test error	1.0865	0.0578	0.0883
Total error	0.9973	0.0405	0.0746
Simulation time (sec)	66.76	199.55	57.25

5.3.1.2 Data pre-processing and data division

After identifying the characteristic of the network structures, the next step is pre-processing the datasets. Figure 83-Figure 85 demonstrate each dataset ‘before’ and ‘after’ normalisation. In the neural network structure, the normalised datasets, which fit in the range of [-1, 1], are utilised. By normalising the neural network inputs, the training is processed efficiently. The first halves of the original datasets are set for training, the third quarters and the fourth quarters are employed in validation and testing stages, respectively.

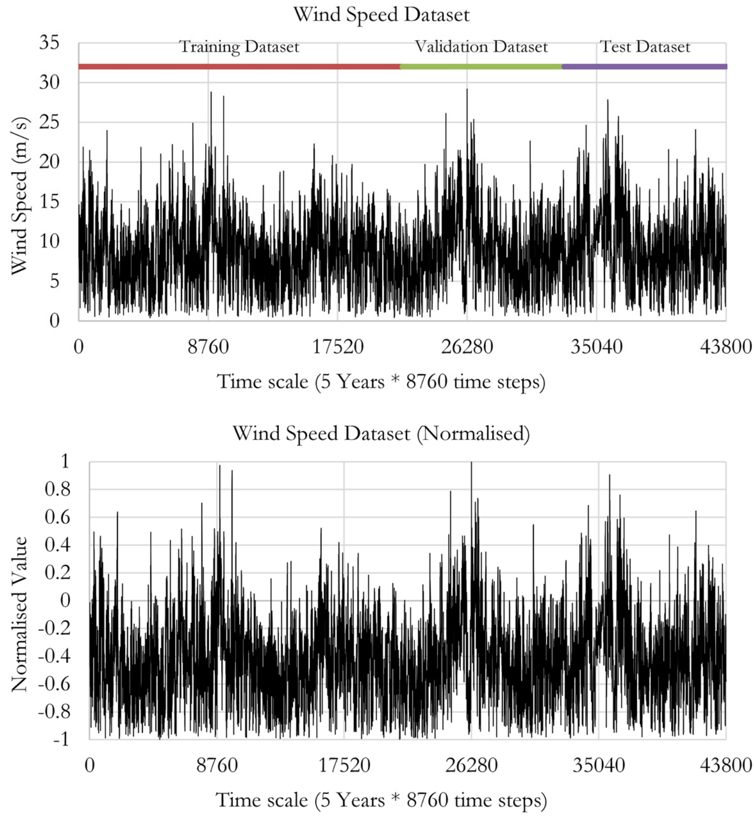

Figure 83: Wind speed dataset – before and after normalisation

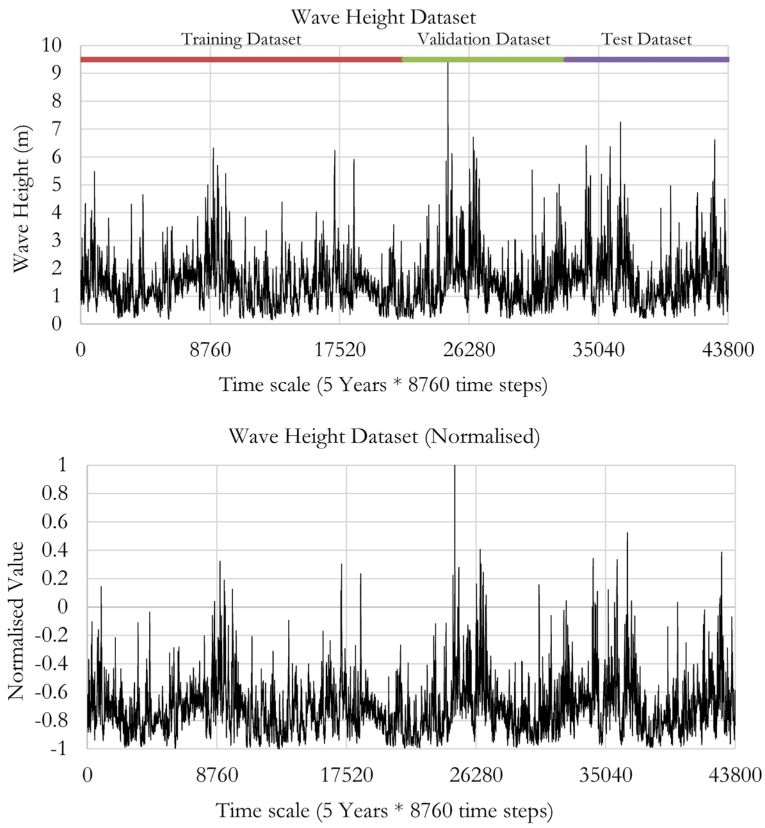

Figure 84: Wave height dataset – before and after normalisation

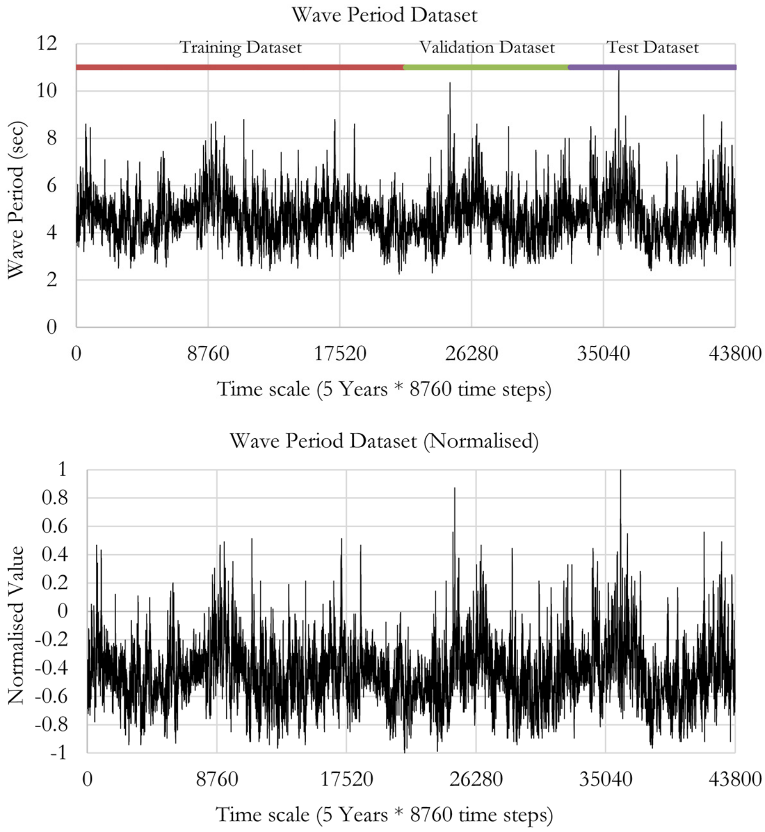

Figure 85: Wave period dataset – before and after normalisation

5.3.1.3 Network training

Individual networks for each dataset are trained in the MATLAB Neural Network Toolbox. Table 30 shows the limiting parameters for the training process. If one of the parameters reaches to its defined limiting value as shown in Table 30, the training continues for 6 more iterations before stopping training. The limiting parameters and their limiting values are adopted from Mark Hudson Beale *et al.* (2014). Figure 86-Figure 88 demonstrate how the training is processed and the decline in the error for each dataset. In these figures, the errors are relatively high and gradually decreases by the optimisation of the network structure in each iteration. For each dataset, μ limiting value is achieved after 45, 10 and 36 iterations. Due to the fact that neural network training is not the main focus of the thesis, the network structures, input weights, layer weights and bias are presented in Table 61-Table 67 in Appendix A.

Table 30: Training limiting parameters

Name	Limiting Value	Definition
Maximum epochs	1000	Number of iterations
Maximum training time	INF	Training time
Error	0	MSE
Minimum gradient	1e-07	Magnitude of the gradient on the error surface
Maximum validation checks	6	The number of successive iterations that the validation performance fails to decrease
μ (Mu)	0.001	The change in the weights for each iteration

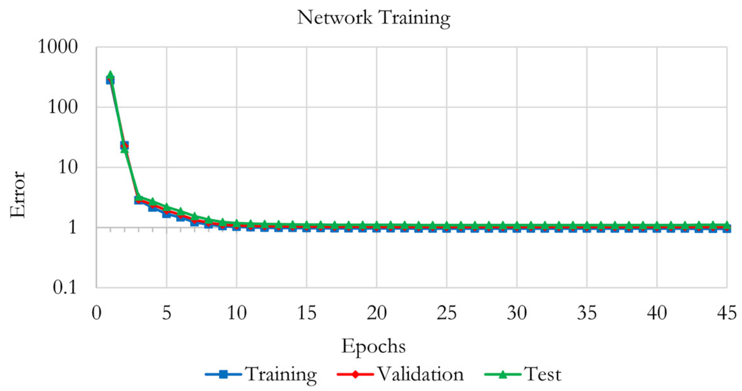

Figure 86: Neural network training – wind speed

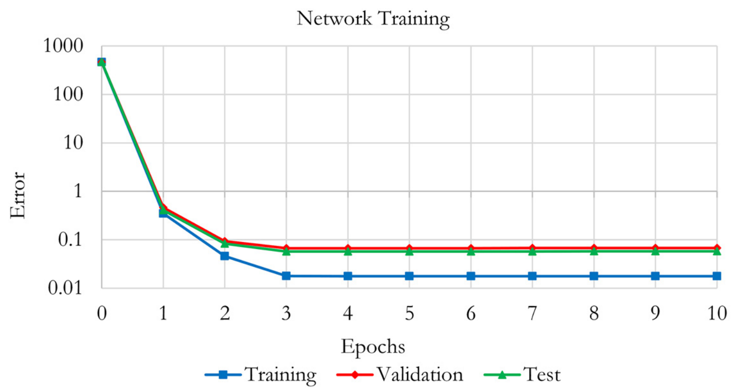

Figure 87: Neural network training – wave height

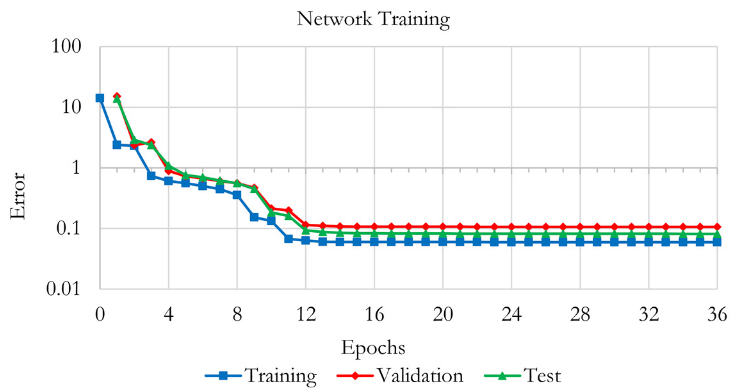

Figure 88: Neural network training – wave period

5.3.1.4 Representative climate dataset generation

After identifying the network structures that represent the wind speed best, wave height and wave period datasets, a unique representative dataset is generated for each operational simulation. In this context, the FINO dataset is divided into 5 datasets (equal in length); all the divided datasets comprise wind speed, wave height and wave period observations together for a period of 1 year. In order to preserve the correlation between wind speed, wave height and wave period observations, these datasets are not disjointed from each other.

Then, a discrete uniform distribution, which defines equal weights on the integers from 1 to 5 (L_{org}), is utilised for random sampling process. In this respect, each integer symbolises one of the pre-divided datasets; thus the selection of an integer indicates the selection of a pre-divided dataset which is represented by that integer. The sampling procedure involves choosing random samples with replacement, which means that every sample is returned to the dataset after sampling. So a particular integer from the original dataset can appear multiple times. Random sampling continues until the number of randomly selected integers becomes equal to 5 (the defined simulation period). The order of the selected integers defines the form of the generated dataset which is utilised in the simulation. This procedure is repeated for each simulation to sustain unpredictability of the climate parameters.

5.3.1.5 Assessment of generated climate datasets

In this section, the generated climate datasets are assessed by comparing the characteristics of original and generated datasets. Due to the fact that interpretation of a figure, which consists of 1000 datasets, is sometimes difficult, the comparisons associated with certain number of datasets are shown in this section. In this context, Figure 89-Figure 91 demonstrate the comparison of distribution of wind speed, wave height and wave period datasets, respectively. In these figures, the red lines denote the original observations and the blue lines denote the generated datasets. These figures show that the distribution of original and generated datasets are alike, however there are minor variations within each simulation. These minor variations can be undesirable from modelling point of view; on the other hand, small variations are acceptable and necessary in order to investigate the operational performance of the vessels and wind turbines under varying climate conditions.

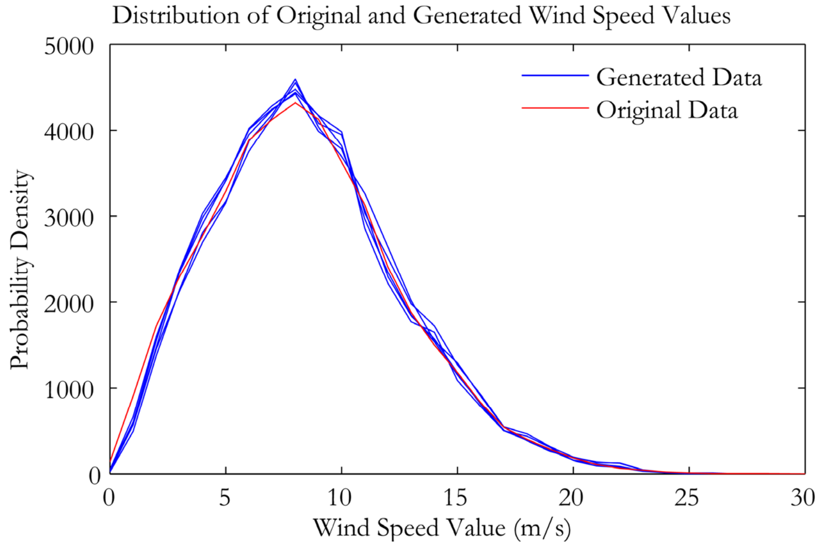

Figure 89: Distribution of original and generated wind speed datasets

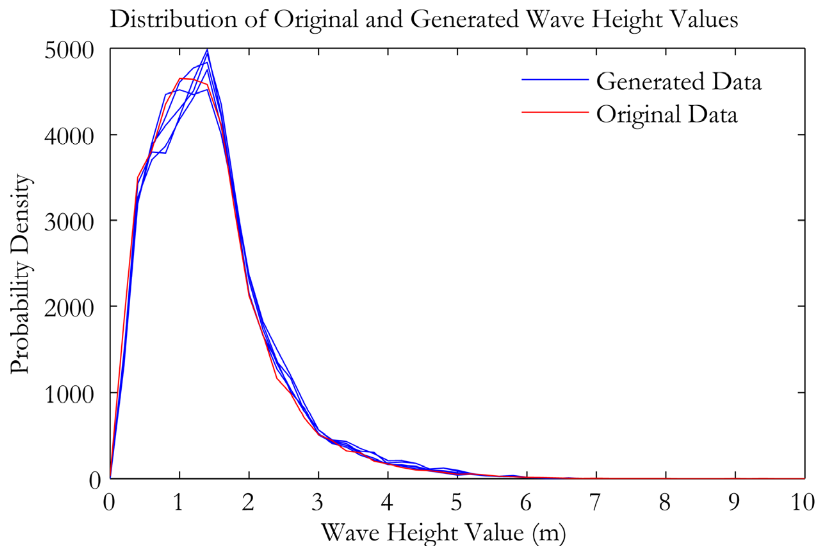

Figure 90: Distribution of original and generated wave height datasets

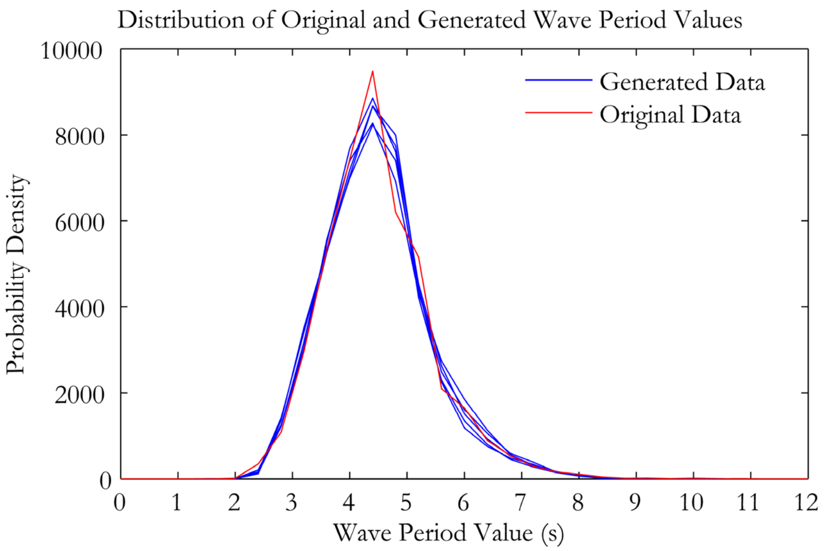

Figure 91: Distribution of original and generated wave period datasets

In addition to distribution of the datasets, the weather window durations considering different wind speed and wave height values are presented in Figure 92 and Figure 93. In these figures, the red lines denote the original observations and the blue lines denote the generated datasets. The wind speed and wave height limits demonstrate the number of occurrence that particular limit is exceeded in consecutive time steps as stated in the horizontal axes of the figures. Therefore, the probability density is higher for lower wind speed and wave height limits. On the other hand, the probability density is lower for longer consecutive time steps. In general, a satisfactory representation is captured by the generated datasets.

Figure 94-Figure 96 show the mean values of the original and generated datasets. The dotted red lines show the mean of the original datasets, while the dotted blue lines show the mean of the 1000 generated datasets. The continuous blue lines show the mean of the each generated datasets. Due to random selection of the inputs, the output datasets show fluctuations in their mean values. In general, the generated datasets have slightly higher means. The level of error in mean values (2.0% or less) is less than the 5% significance level. The modelling errors in the definition of neural network structure are the main causes of the observed errors in the overall mean values. In order to elaborate the assessment, the monthly mean values are also presented in Figure 97-Figure 99. In these figures, the red line shows the monthly means of the original datasets; the box-plots are the representation of how the generated datasets are distributed. As intended in the methodology, variations are achieved in the monthly values, so it will be possible to simulate good weather years and bad weather years by the developed methodology.

The correlation coefficients shown in Figure 100-Figure 102 are the measures of the strength and direction of the linear relationship between two variables (wind speed-wave height, wind speed-wave period, wave height-wave period). The correlation coefficient ranges from −1 to 1. A value of 1 implies that a linear equation describes the relationship between two variables perfectly, with all data points lying on a line for which the first dataset increases as the second one increases. A value of −1 implies that all data points lie on a line for which the first dataset decreases as the second one increases. A value of 0 implies that there is no linear correlation between the variables. In this context, the relations between 'wind speed and wave height' and 'wave height and wave period' are more significant than the relation between 'wind speed and wave period' for both original and generated datasets. In general, a satisfactory representation is captured by the generated datasets.

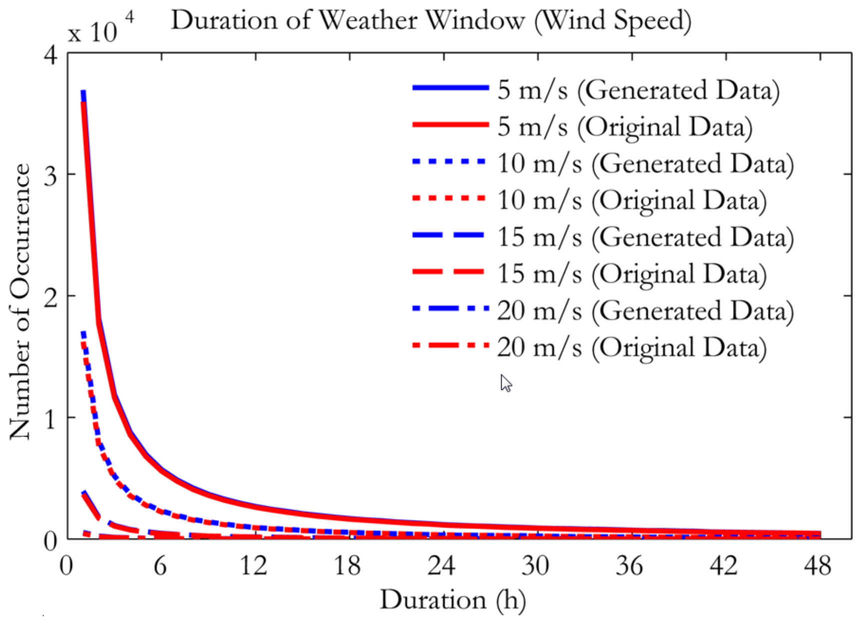

Figure 92: Duration of weather window (wind speed)

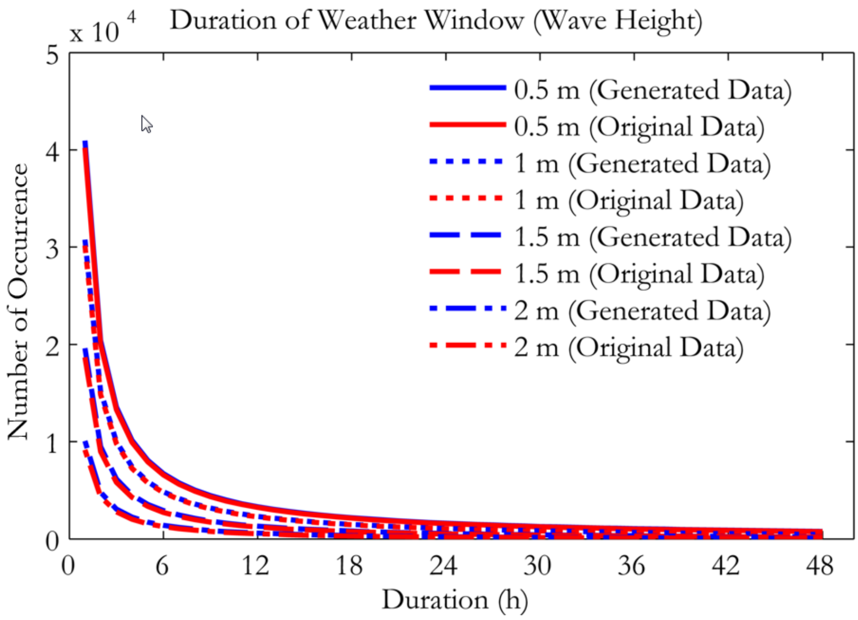

Figure 93: Duration of weather window (wave height)

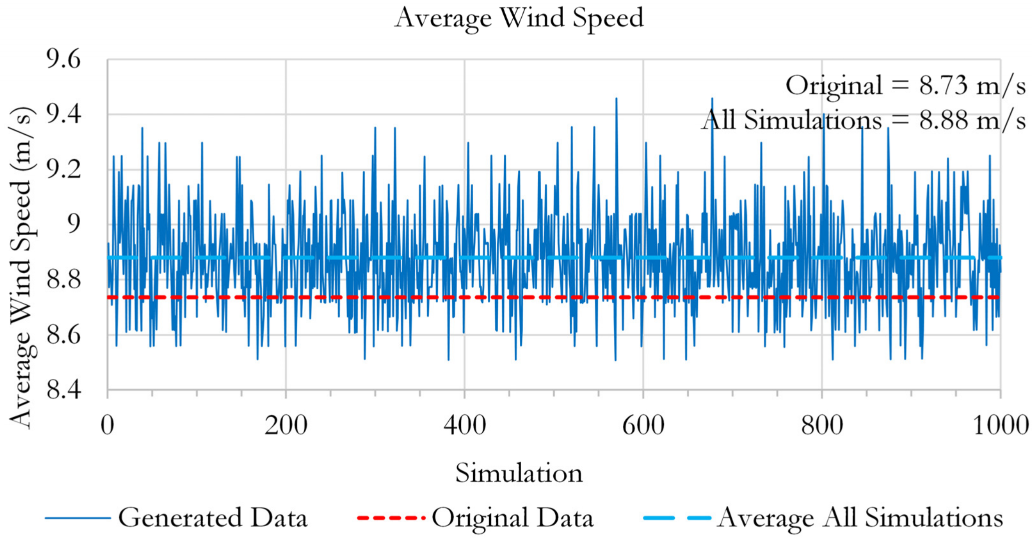

Figure 94: Average wind speed

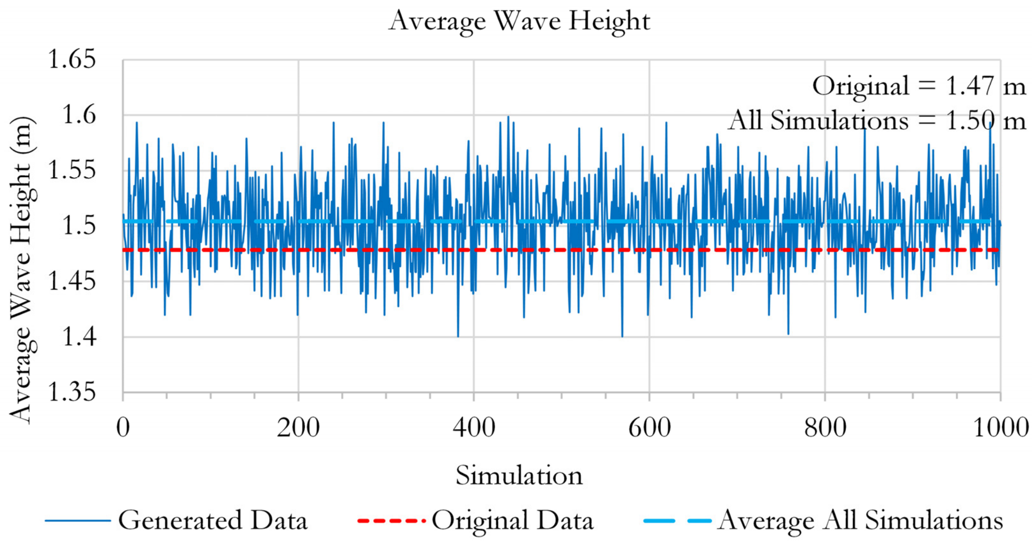

Figure 95: Average wave height

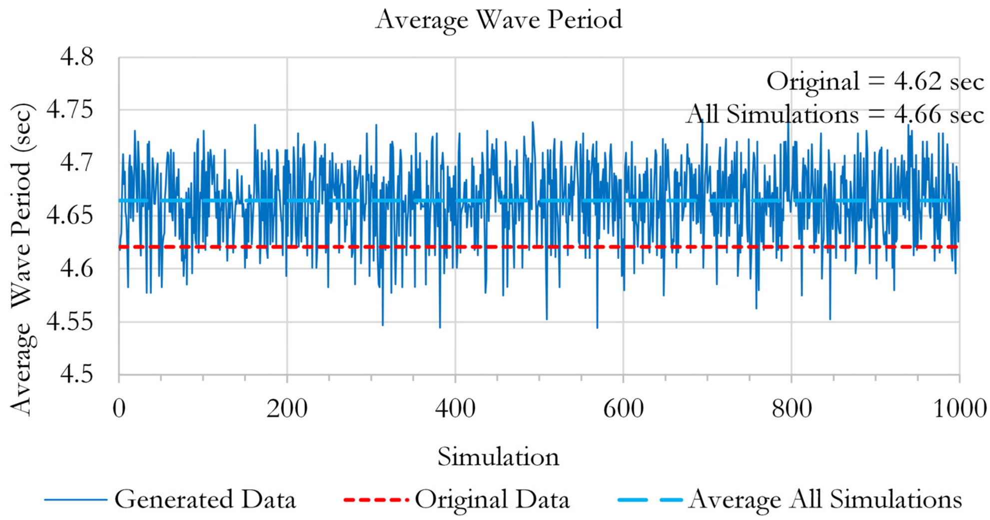

Figure 96: Average wave period

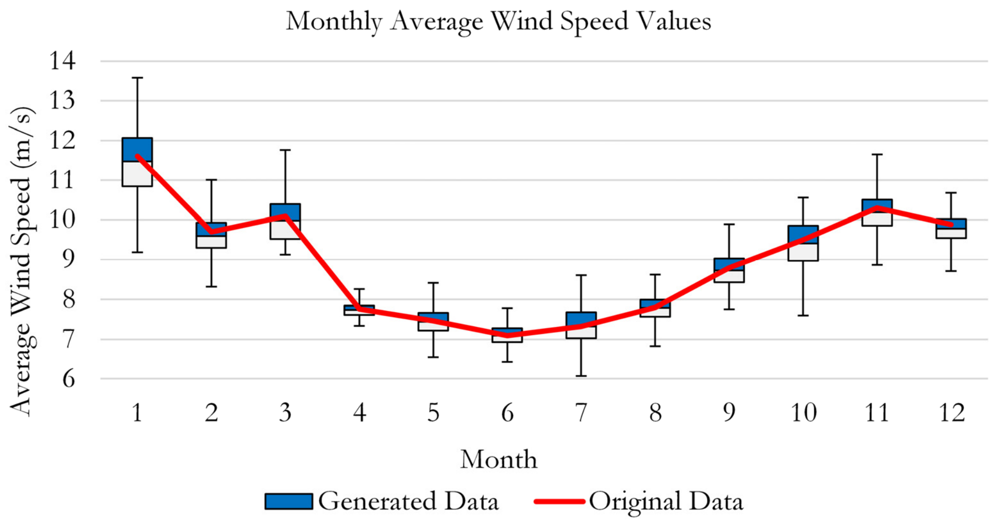

Figure 97: Monthly average wind speed values

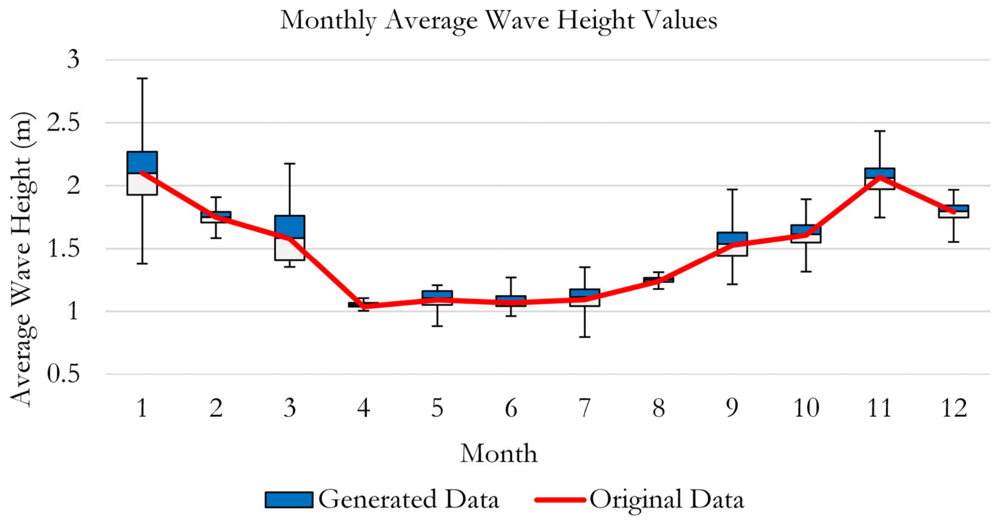

Figure 98: Monthly average wave height values

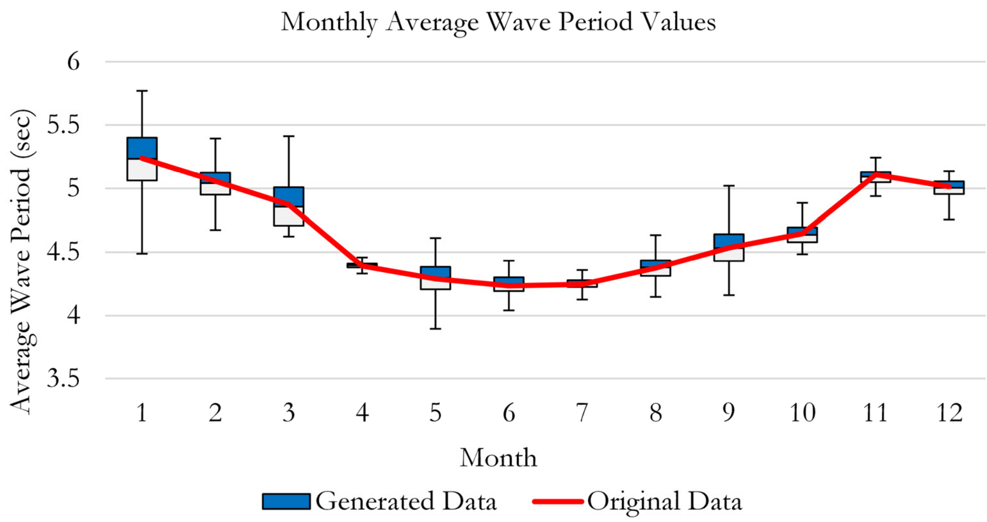

Figure 99: Monthly average wave period values

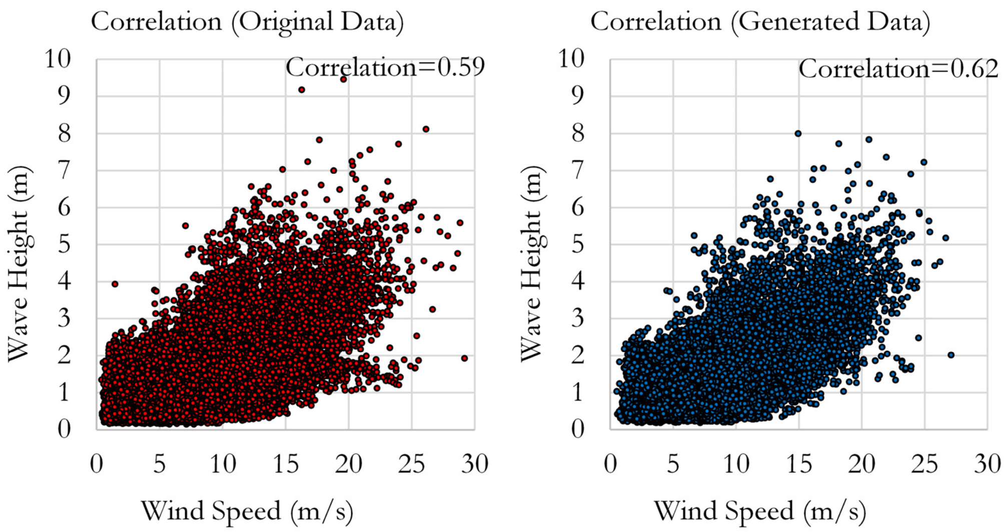

Figure 100: Comparison of correlation coefficients (wind speed – wave height)

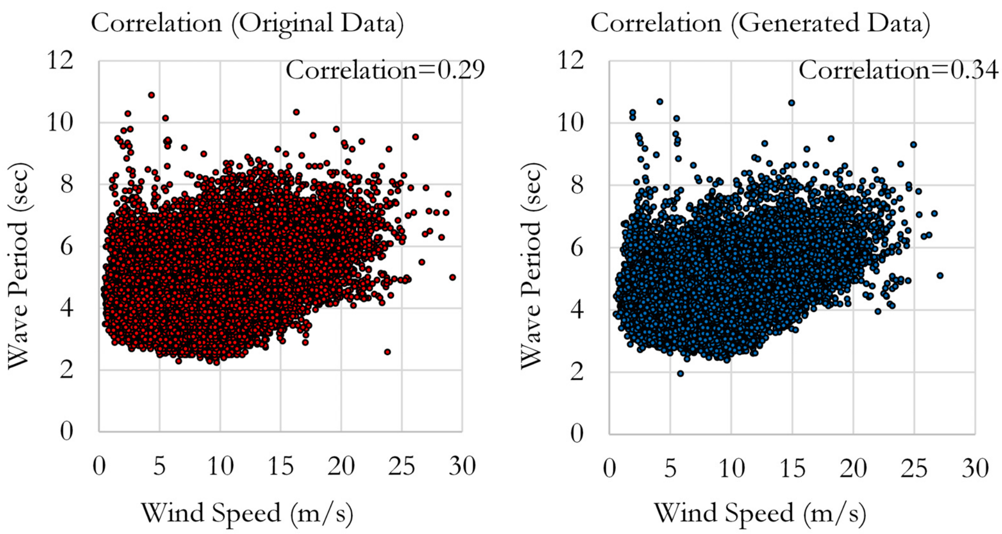

Figure 101: Comparison of correlation coefficients (wind speed – wave period)

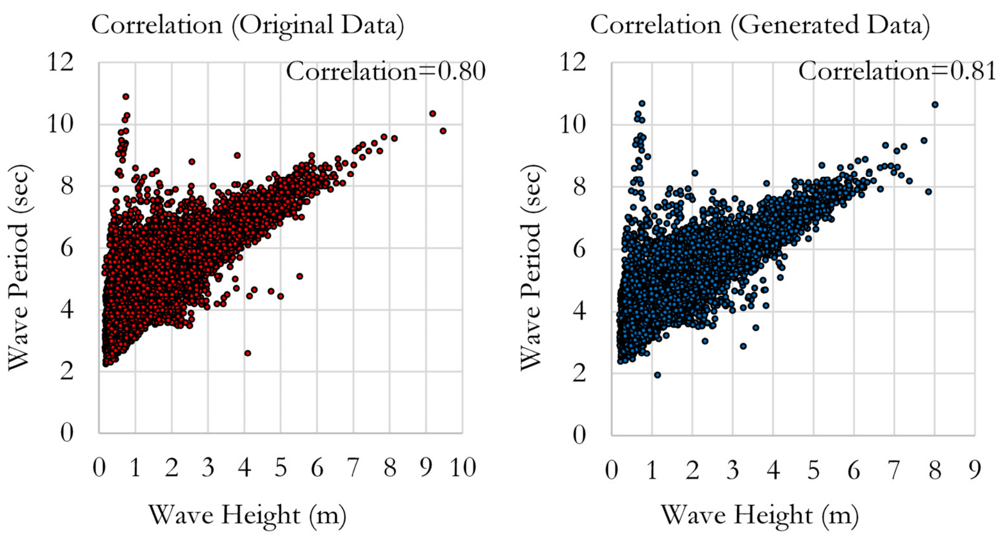

Figure 102: Comparison of correlation coefficients (wave height – wave period)

5.3.2 Vessel accessibility analysis and transit time calculation block

Figure 103 shows the simulation phase, which is explained in the section. In order to demonstrate a clear framework, the box associated with this section is highlighted and other boxes are made transparent.

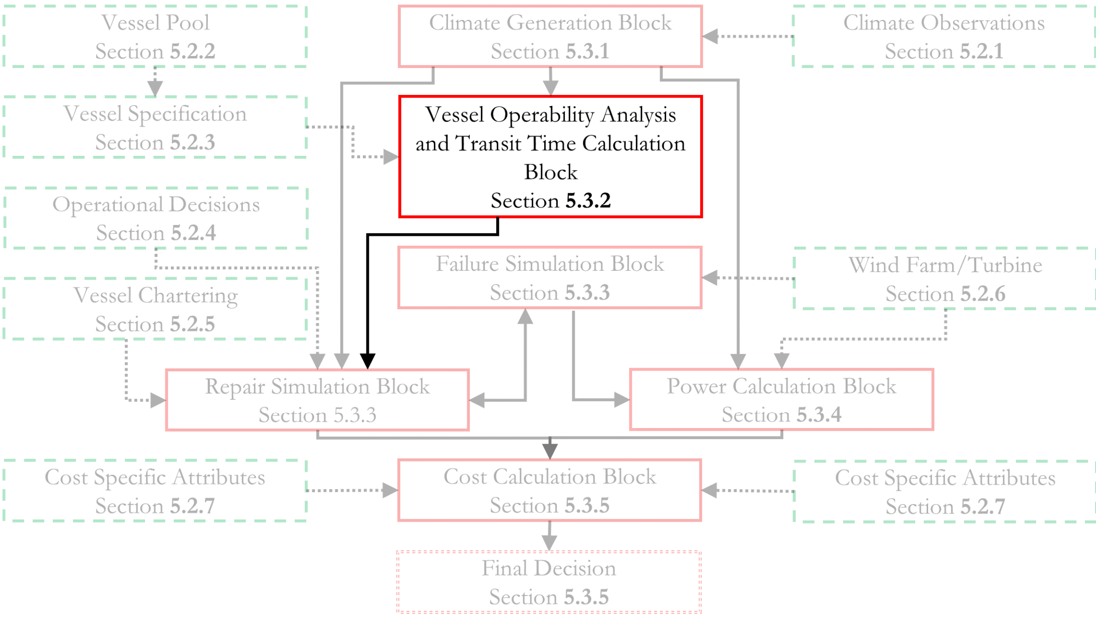

Figure 103: Definition of simulation phase

5.3.2.1 CTV analysis

In this section, the accessibility of the O&M fleet and transit time calculations are performed. Due to the fact that climate conditions vary from day to day, the accessibility analysis and transit time calculation have to be performed on a daily basis. In the thesis, a single working shift is considered for the CTV operations; therefore, the climate conditions between 8 a.m.-8 p.m. are especially important. In this respect, it is envisaged that a CTV can leave the O&M port at 8 a.m. and this CTV has to be back at 8 p.m. Due to daylight limitation, the technician allocation may need be suspended until the sun rises, and similarly, the working shift may need to be ceased earlier, if the sun sets before 8 p.m. The daylight limitation is an important measure that limits the operations especially in northern countries during winter. In this respect, Figure 104 shows the sunrise-sunset times and the maximum length of working shift in the wind farm throughout the year. In order to consider dawn and dusk periods, a period of 1 hour (30 minutes for dawn and 30 minutes for dusk period) is added to the length of a working shift. It can be seen that the length of shifts in winter is significantly shorter than its usual value of 12 hours. In this period, although the CTVs can travel during the night, the technician allocation can only be performed after the sun rises and before the sun sets. The length of the working shift can be maximised to 12 hours between March and September.

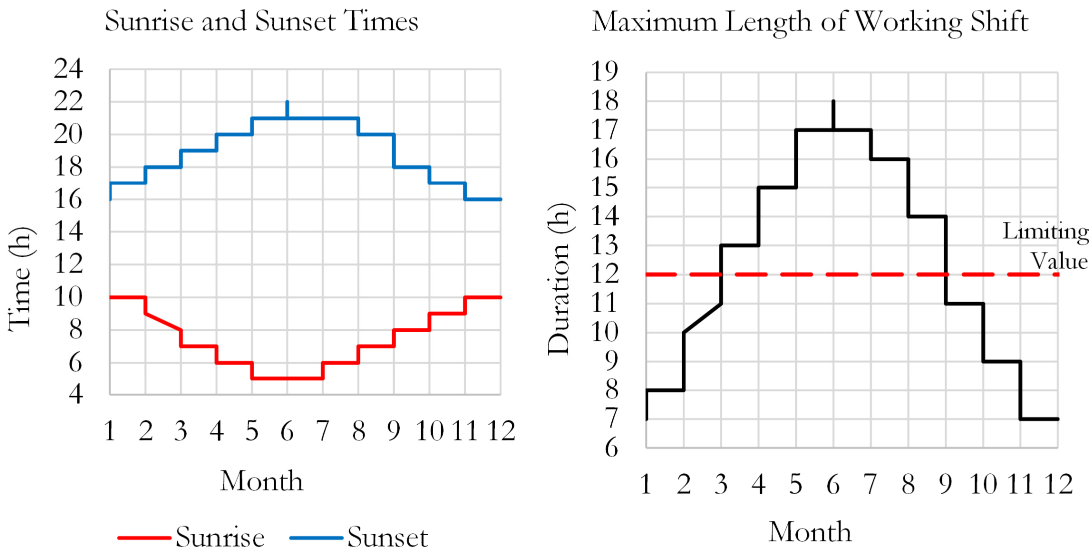

Figure 104: Sunrise-sunset time and maximum length of working shift

- Calculation of speed loss

In the case study, the catamaran configurations are analysed as two separate monohull vessels. The resistance calculations are performed for the monohull vessels and the results are multiplied by 2 in order to calculate the total catamaran hull resistance. The calm water resistance of the CTVs are presented in Table 31 by assuming the propeller efficiency as 60%. Due to increase in the wetted surface, the 26 m CTV has the highest calm water resistance among all the CTV types.

Table 31: Calm water resistance

	26 m WFSV	21 m WFSV	17 m WFSV
Resistance	37,124 N	33,204 N	31,594 N

After calculation of the calm water resistance, the added resistance and speed loss for each time step is calculated by equations provided by Jinkine and Ferdinande (1973) and Berlekom (1981). In this respect, Figure 105 shows the level of operability for each CTV type and the mean speed values in the operable days. The operability of the vessel indicates the proportion of 'the time steps that the CTV engines can move the vessel in the sea' to 'the total number of simulation time steps', neglecting the limiting climate conditions. It can be seen that the level of operability is significantly high (above 90%) for all CTV types. Due to its slenderer body, the smaller CTV provides better operability than the larger CTVs. On average, 20%, 16%, and 21% of speed loss is expected for each CTV type during simulations. The vessel accessibility can be calculated by also applying the limiting climate parameters.

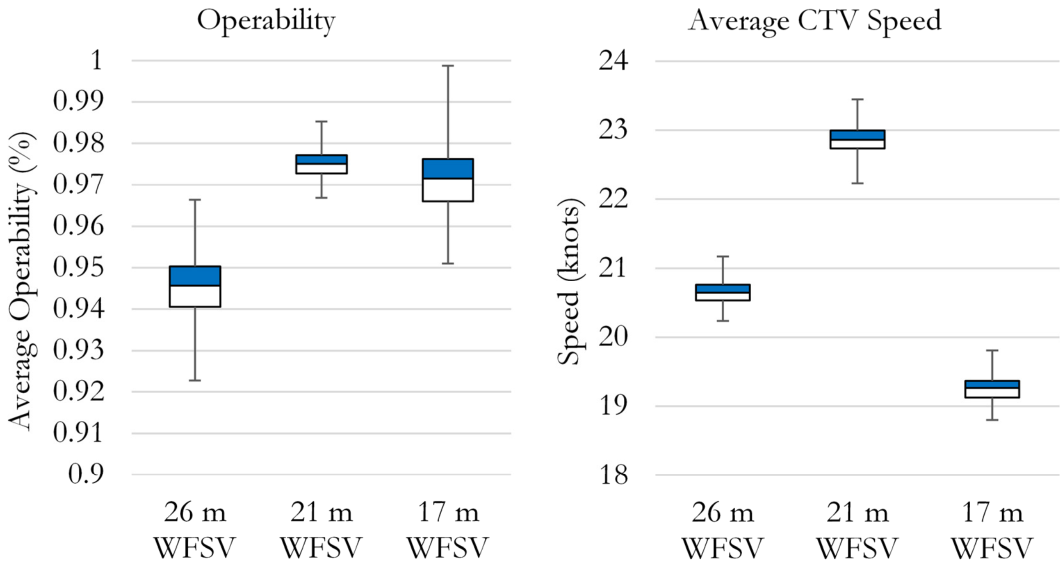

Figure 105: Operability and average CTV speed in operable days

The level of accessibility is considerably lower than the level of operability (Figure 106). This is because, the limiting climate parameters cause major terminations in the technician allocation. The accessibility demonstrated in Figure 106 is the absolute CTV accessibility, in which limiting wind speed, limiting wave height, operational weather window, maximum productive period and daylight period in repair days are considered. For offshore wind farm O&M, the vessel accessibility is more important than the vessel operability; because even though the vessels can operate in harsh conditions, if the technicians cannot be allocated to the turbine, the core maintenance activity cannot be completed. The mean CTV speed values are slightly increased after the application of limiting climate parameters. The vessel speed is expected to be lower in harsher conditions; by implementing the limiting climate parameters, the lower vessel speed values are eliminated; therefore, the mean speed values in accessible days are slightly higher than the mean speed values in operable days.

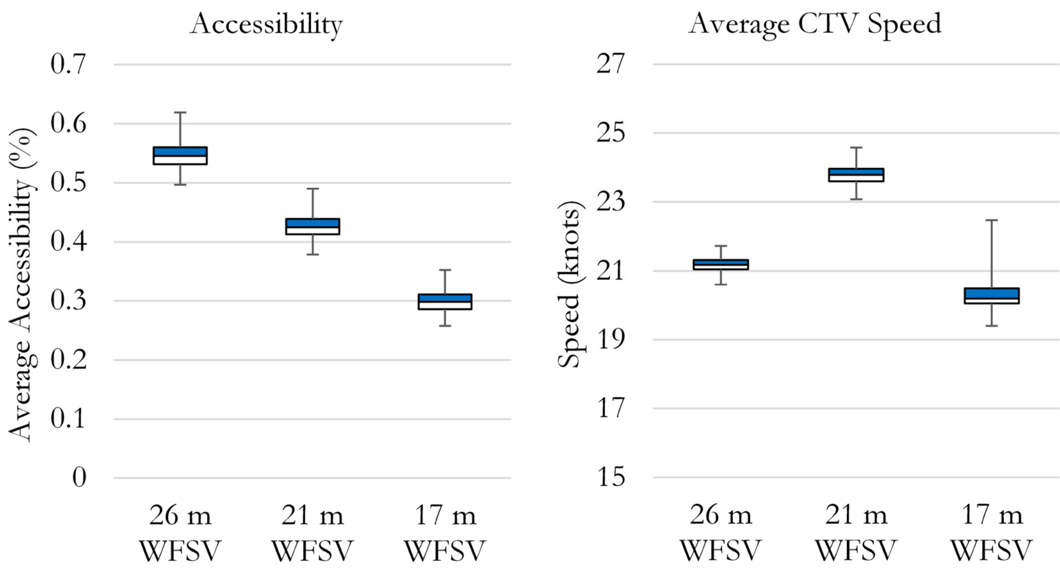

Figure 106: Accessibility and average CTV speed in accessible days

The difference between the operability and the accessibility of the CTVs becomes more noticeable when the monthly values are investigated as shown in Figure 107-Figure 109. The operability of all the CTV types are above 95% in summer months and above 75% in winter months. On the other hand, there is a very large variability in the accessibility results among different months for the same CTV type and among all CTV types for the same period in a year. There is a significant difference between summer and winter months in the level of accessibility for each CTV type. Even for the 26 m WFSV, the accessibility can drop to 10% in winter, while the lowest summer accessibility is expected to be around 60%. The results are poorer for the 17 m WFSV, since the summer availability can drop below 40%. The critical aspect about 17 m WFSV is the 0% accessibility in some of the winter months. The is critical, because when the accessibility is 0%, there is no chance that the O&M technicians can be allocated to failures regardless of the CTV fleet size. Even in very low accessibility cases, the power production can be sustained by a relatively large CTV fleet; however 0% accessibility indicates that failures remain unrepaired for a long time and therefore, drastic power production loss and subsequently financial loss is expected. Due to harsher conditions, the monthly average speed values in winter are also lower than the values in summer. The maximum continuous operational speed of the 21 m WFSV is higher than the other CTV types; therefore, the monthly average values are also higher, but the generic trends are alike (high in summer, low in winter).

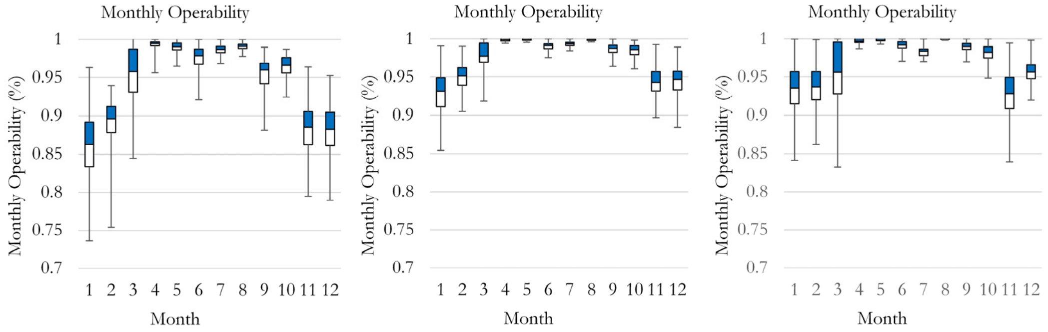

Figure 107: Monthly operability

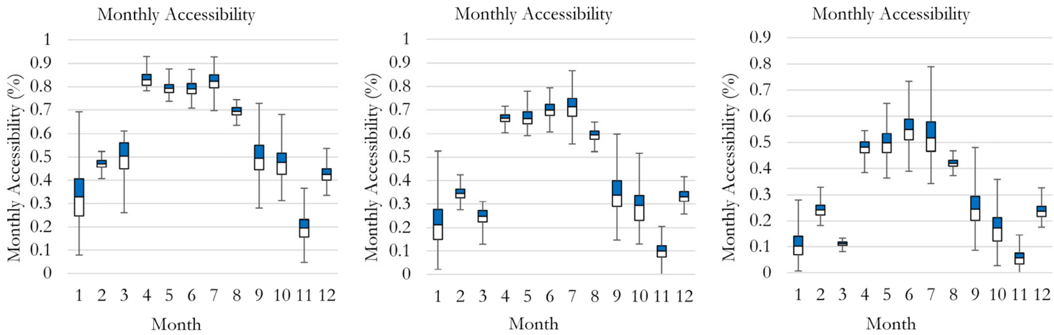

Figure 108: Monthly accessibility

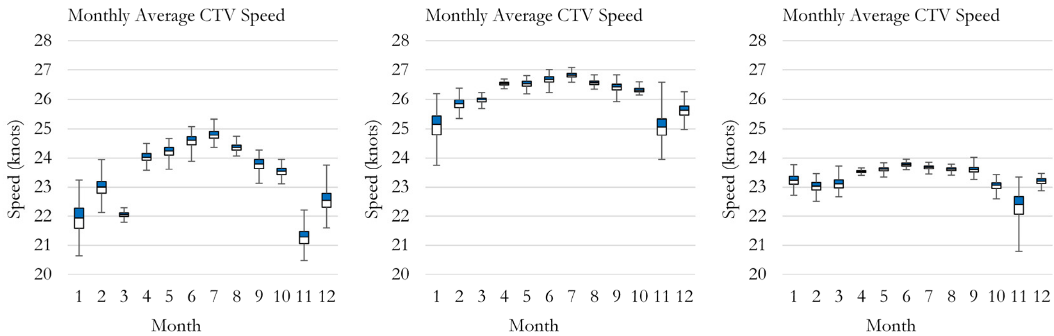

Figure 109: Monthly average CTV speed

5.3.2.2 Jack-up vessel analysis

Jack-up vessel operations are performed in different heights and therefore, the climate conditions at these altitudes are important to capture. Table 32 summarises the 3 major stages of jack-up vessel operations and associated limits. Considering the wave height is a variable that is observed in a single altitude (sea level), only wind speed observations at observation height are altered to sea level (10 m) and nacelle level. Figure 110-Figure 112 show the maximum, average and minimum wind speed in each month before and after height adjustment. In this respect, the wind speed values at sea level are lower than the values at the observation height. Similarly, the wind speed values at observation height are lower than the values at the nacelle level. The trend, in which the summer wind speed values are lower than the wind speed values, is preserved in both altitudes after alteration. These graphs also show that a 4 m/s wind speed difference that can be expected between sea level and nacelle level. This is a significant difference, which can be bigger for larger turbines and this needs to be captured in order to model the lifting operations and power production calculations in an accurate way. The values at sea level are crucial for the jacking-up and jacking-down operations. The jack-up vessel survivability is also investigated by analysing the wind speed value at sea level. If the jack-up vessel can jack up, then the lifting operations are affected by the wind speed values at nacelle level.

Table 32: Jack-up vessel operational stages

Limit Name	Associated Operation	Limiting Value	Stage 1 Jacking up	Stage 2 Operation	Stage 3 Jacking down
Wind speed at sea level	Jacking up/down	15.3 m/s	✓	-	✓
Wave height	Jacking up/down	2.8 m	✓	-	✓
Wind speed at hub level	Operability	20 m/s	-	✓	-
Wind speed at sea level	Survivability	36.1 m/s	✓	✓	✓
Wave height	Survivability	10 m	✓	✓	✓

Figure 113 shows the proportion of the time steps that either wave height or wind speed values remain below the survivability limits to the total number of time step in that particular month. Survivability is the priority in any operation, because if there is a risk of storm, the jack-up vessel cannot stay at the offshore wind farm; therefore, the vessel needs to be transferred to a safe place. In this context, the survivability limits of the jack-up vessel are considerably high, therefore, 100% jack-up vessel survivability is expected within all the simulations. 100% survivability indicates that when the jack-up vessel is charted either for short-term or long-term, the vessel can operate without any interruption due to a storm. At this stage, it is important to highlight that the FINO dataset utilised in the simulations covers a 5-year period, and the original observations are far below the survivability limits of the jack-up vessel. Considering the fact that a storm can occur rarely, the survivability can drop below 100%, if a larger dataset (i.e. a period of 100-years) is covered.

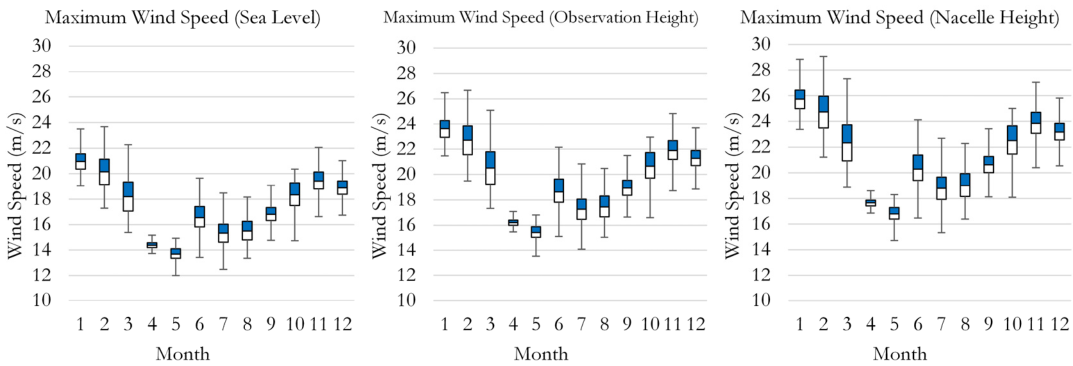

Figure 110: Alteration of wind speed to different altitudes (maximum values)

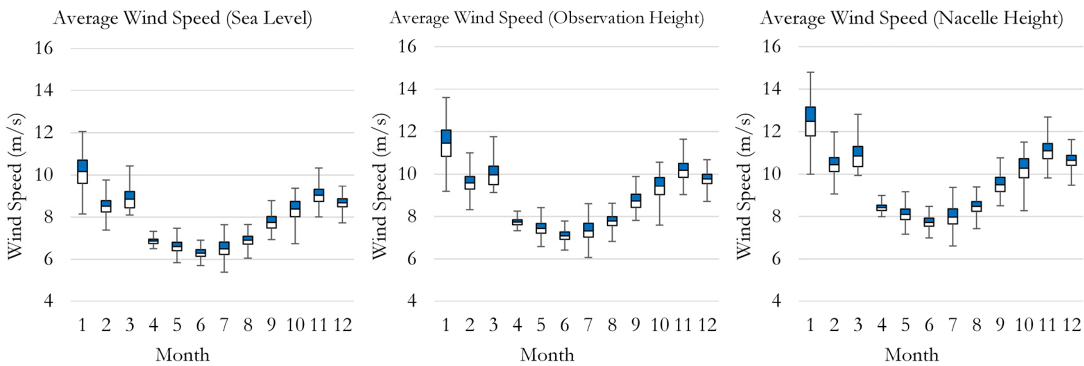

Figure 111: Alteration of wind speed to different altitudes (average values)

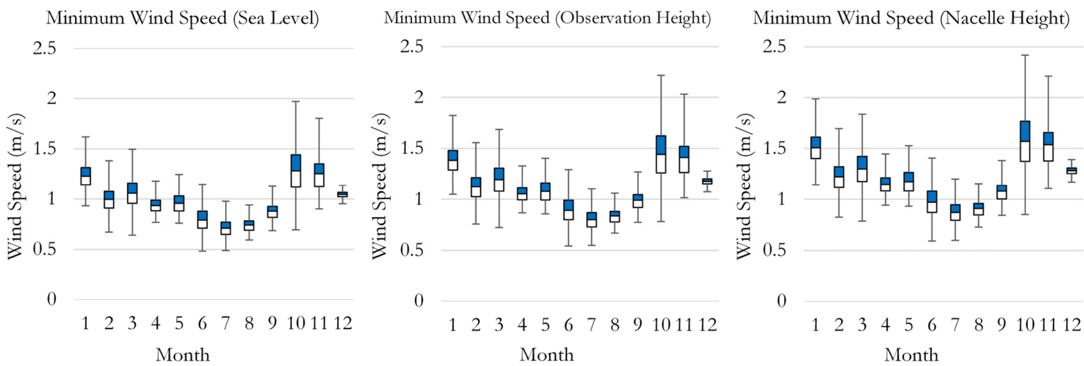

Figure 112: Alteration of wind speed to different altitudes (minimum values)

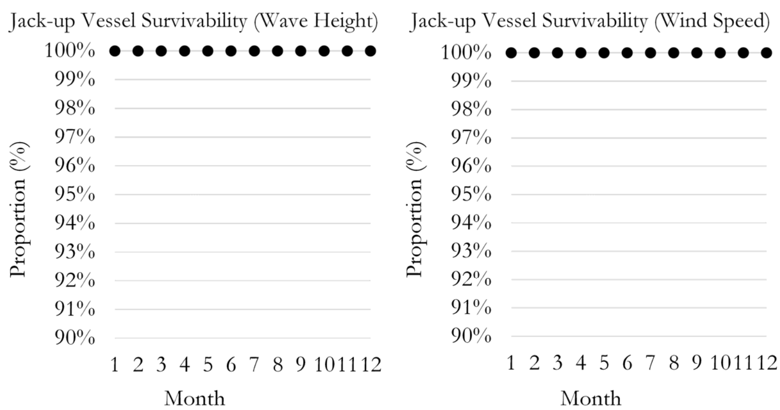

Figure 113: Jack-up vessel survivability

Thereafter, Figure 114 shows how likely that the jacking-up and jacking-down operations can be performed within a month. In this context, the wave height and wind speed limitations at sea level are taken into account. In addition to individual investigations, a combined wave height-wind speed limitation is also considered. The combined limit investigation is crucial, because there can be cases that either of the observations can result in interruptions. In this case, even only wind speed value or wave height value exceeds the limits, the operations need to be ceased. On the other hand, individual investigations are also important in order to identify what the main driver or key limitation is in the jack-up operations. In this case study, a 3-hour weather window is required to complete a jack-up operation; therefore, 3 consecutive time steps, in which the climate parameters are below the jack-up limits, are sought. Due to the challenging climate conditions in winter, the probability of completing a jacking-up operation can be below 50%. Summer is a considerably better period for jack-up operations, because it is unlikely that the operations can be ceased due to weather.

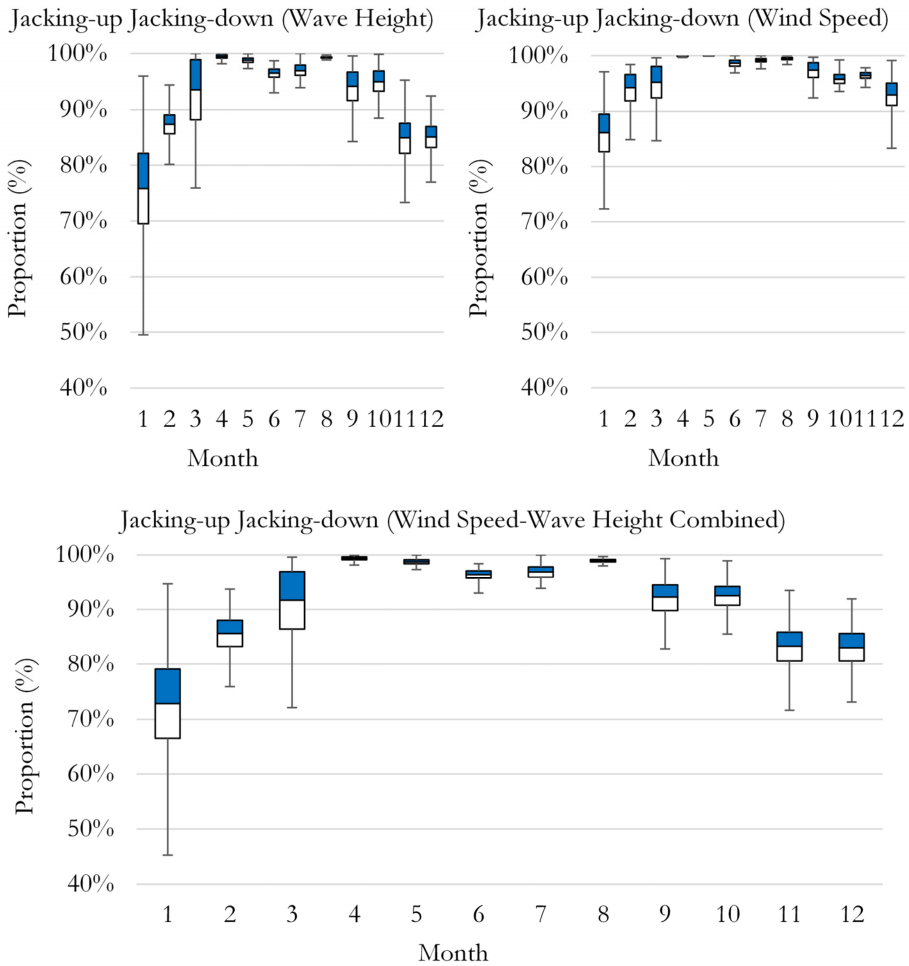

Figure 114: Jack-up jack-down operations

The main driver in the jacking-up operations is the wave height limitation; this can be noticed by comparing the top two graphs (wind speed and wave height, separately) in Figure 114 and their contribution to the graph below (wind speed-wave height combined) in Figure 114. It can clearly be seen that the individual influence of the wave height is more dominant than the influence of the wind speed. The reason why the combined limit values are not equal to the summation of each parameter is the time window that both wind speed and wave height do not allow jacking-up operations.

Due to the fact that jack-up vessel provides a stable platform for the lifting activities, the maintenance operations are not influenced by waves anymore, unless wave height observations are below the survivability limits of the jack-up vessel. Considering the fact that wind speed values are higher at nacelle level, these observations are taken into account. In this respect, Figure 115 demonstrates the probability of completing the lifting operations in 1-day, 3-days, 5-days and 7-days of weather window. The probability of having a sufficient weather window decreases by the increasing periods. It is likely to have a 1-day weather window during the whole year; however when a 7-days weather window is required, the probability can decrease to 10% in January. Among all weather window periods, summer is the preferred option over winter. The probability of having a complete weather window is always higher in summer than the probability in winter. These results clarifies why wind farm operators plan major component repairs during summer and also why the vessel operators keep the charter rates low in winter. The level of available weather window leads the jack-up vessel supply-demand balance in the offshore wind O&M market.

The length of operational weather window is a crucial aspect, because jack-up vessels are responsible for the lifting of heavy components such as a blade and a generator. If the weather becomes bad during a lifting operation, this can have adverse consequences such as component loss, injury or casualty, etc. Therefore, it is very important to plan the lifting operation in full available weather window. As for all the vessel operations, lifting is also restricted during winter and the probability of having a sufficient period decreases when the required weather window becomes longer. A 7-days or longer weather window may not be necessary for normal circumstances; however, there is always a risk that the O&M activities can take longer than initially planned. Therefore, a safety margin always need to be considered for jack-up lifting operations.

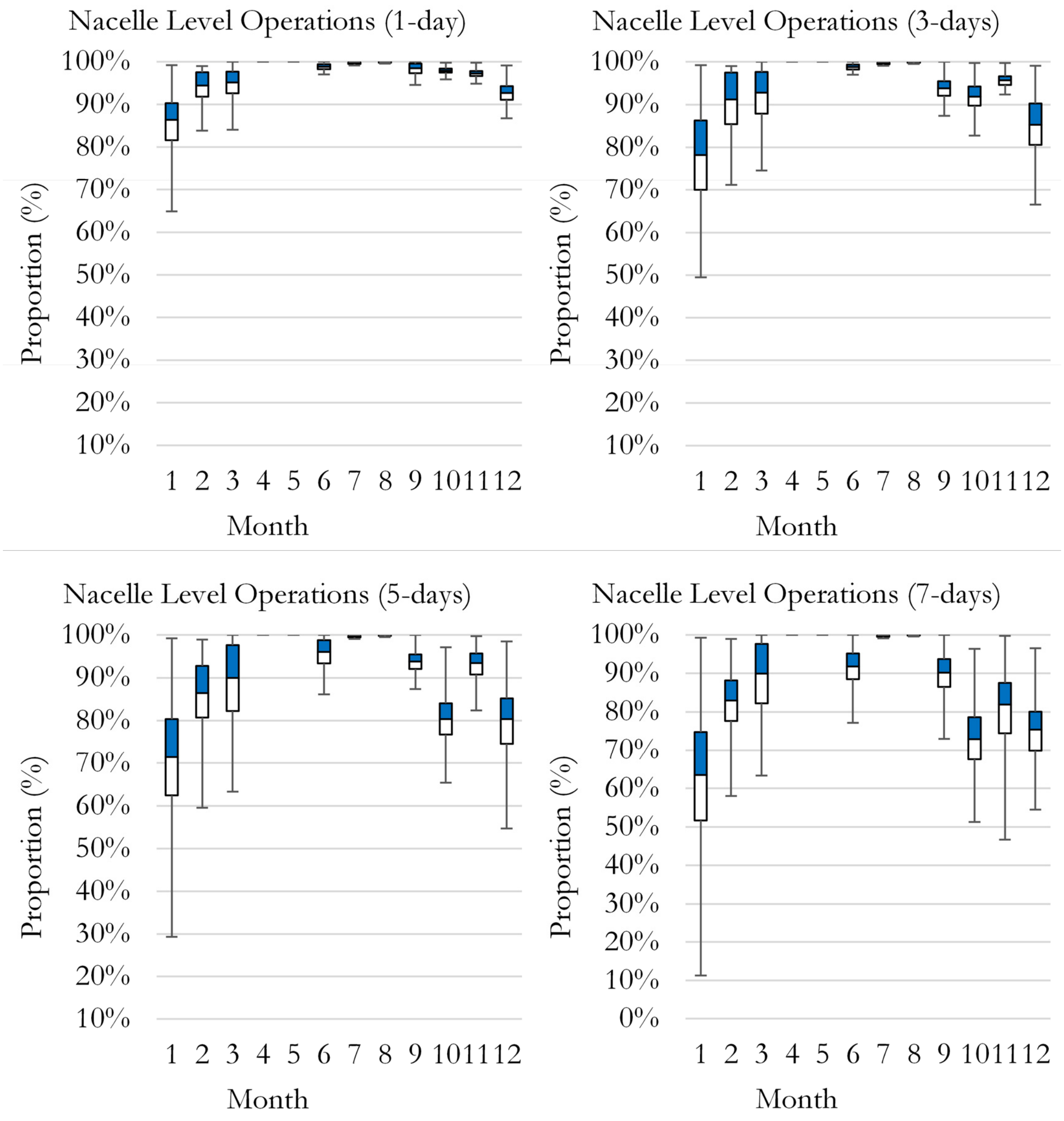

Figure 115: Lifting operations

5.3.3 Failure and repair simulation blocks

Figure 116 shows the simulation phase, which is explained in the section. In order to demonstrate a clear framework, the box associated with this section is highlighted and other boxes are made transparent. Figure 117 demonstrates the alteration in the failure rates for an example turbine in a simulation. The initial failure rates are the values defined at the beginning of the simulations. It is assumed that the condition of the turbine components is considered 'as good as new' after a repair activity; therefore, alterations are noticed in the simulated (updated) failure rates compared to initial failure rate distribution. At this stage, it should be highlighted that the alterations in this figure and the information provided in Table 33 are unique for this example turbine and this simulation. In a single simulation, 140 turbines (number of turbine defined for the case study) are simulated separately; therefore, each turbine has an individual updated failure rate distribution. Furthermore, this procedure is repeated for each simulation, so, the number of distributions generated in the case study is equal to the multiplication of the number of turbines and the number of simulations.

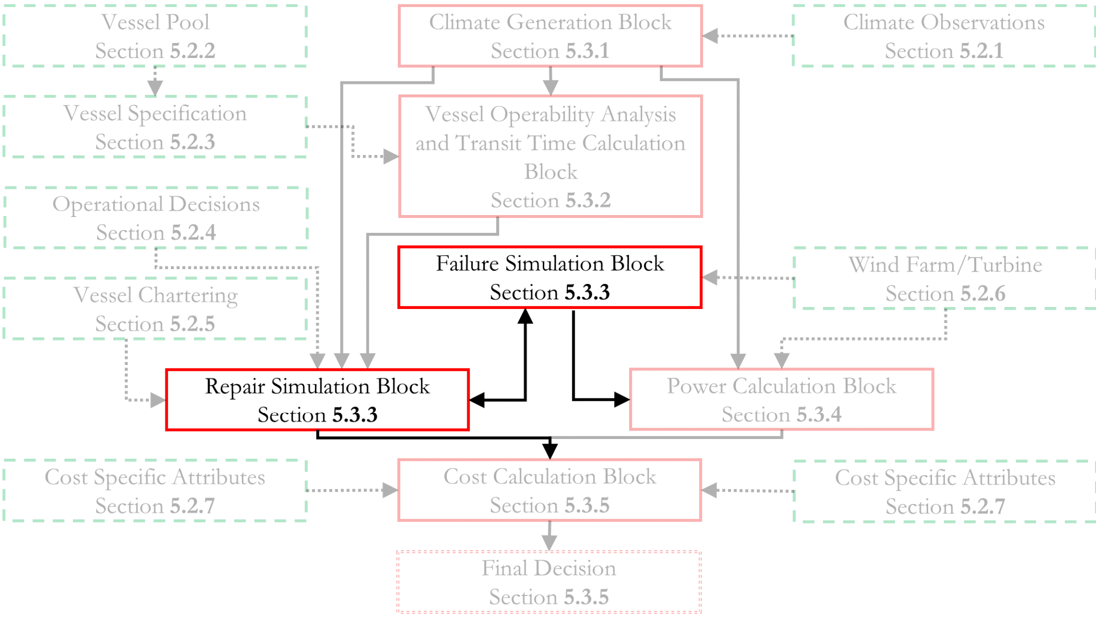

Figure 116: Definition of simulation phase

In Figure 117, all the thin colourful lines represent a turbine component and the thick black line represents the overall turbine system failure rate. Initially, the turbine system is assumed as a series of sub-systems, therefore, turbine system failure rate comprises of the summation of turbine component failure rates. After each failure, the failure rate of the failed component and the overall turbine failure rate are updated. Detailed failure information associated with this particular turbine is provided in Table 33. 39 failures are occurred in this turbine within 5 years and 38 of these failures are categorised as a minor failure. The components with higher failure rate failed more frequently than the components with lower failure rate. Due to fixed failure rate, an alteration in the sensor failure rate cannot be noticed in Figure 117; instead, Table 33 is provided for detailed failure information.

At the end of year 3, there is a major failure in the gearbox, the change in the failure rate is marked with a red dashed ellipse at the bottom of this figure. Due to jack-up vessel mobilisation (marked with an amber dashed ellipse at the top of the figure), this turbine remained in failed condition for 3856 time steps (~160 days). The failure rates of the other components when the turbines start functioning are equal to the failures rates at the failure time step; on the other hand, the failure rate of the failed component is reset. Due to the fact that the turbine system failure rate is equal to summation of individual component failure rates, the turbine system failure rate is updated after each repair.

Due to updates on the failure rates during simulation, a difference is noticed in the overall failure rates. At the end of year 5, the failure rates are not as low as initially planned and therefore, the number of failures is more likely to be higher than expected in the future. Initially, the overall turbine failure rate at the end of year 5 is estimated as 6 failures/year; however, it is just below 8 failures/year. Moreover, the period that the turbine remained in failed condition is significantly higher than the actual repair periods defined. This difference is generally associated with inaccessibility for minor repairs and jack-up vessel mobilisation (or jack-up vessel unavailability) for major failures.

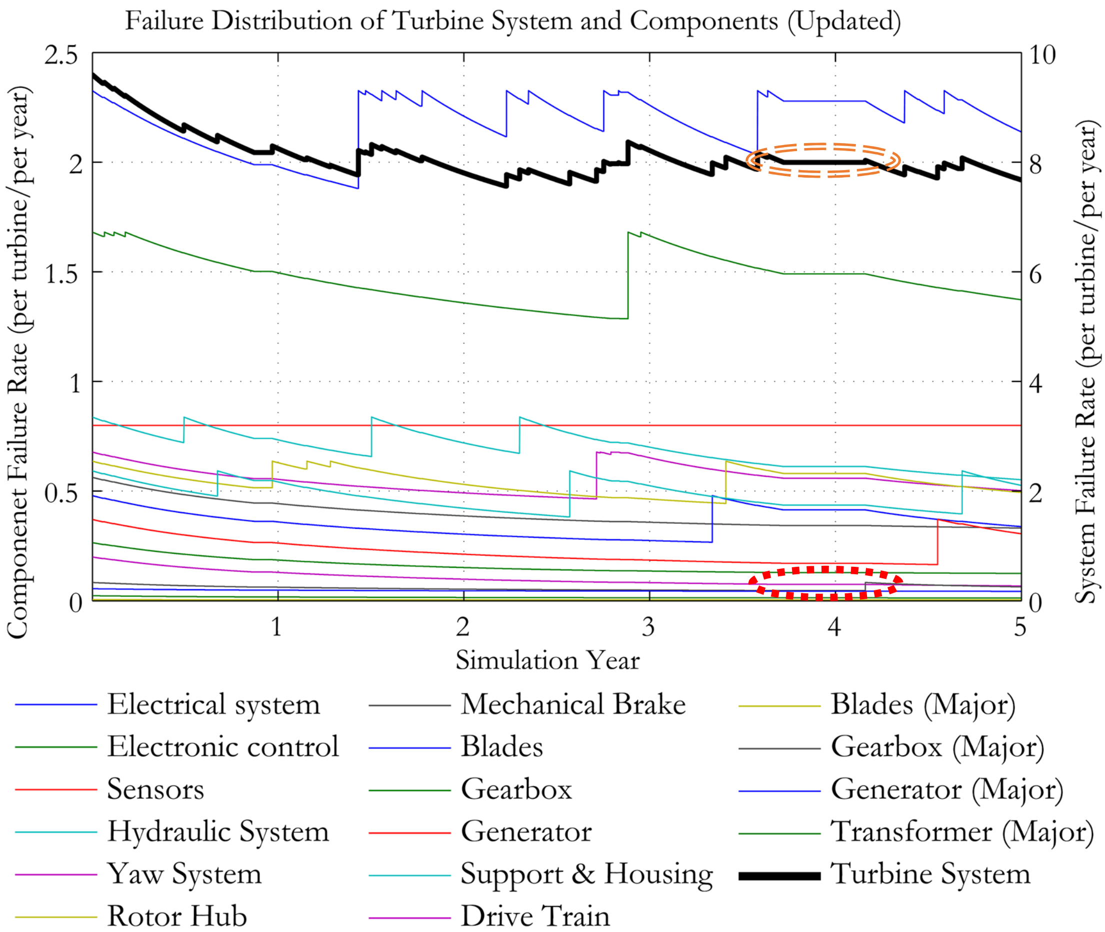

Figure 117: Alteration in failure rates

Table 33: Failure information

Failure Mode	Failure Time Step	Failure Day	Failure Year	Access Type	Repair Time Step	MTTR
Electronic cont.	485	21	1	1	567	82
Electronic cont.	964	41	1	1	1021	57
Electronic cont.	1534	64	1	1	1553	19
Hydraulic System	4286	179	1	1	4313	27
Support-Housing	5873	245	1	1	5897	24
Rotor Hub	7643	319	1	1	8485	842
Rotor Hub	10019	418	2	1	10117	98
Rotor Hub	11187	467	2	1	11225	38
Electrical system	12492	521	2	1	12545	53
Sensors	12779	533	2	1	12810	31
Electrical system	12854	536	2	1	12881	27
Hydraulic System	13145	548	2	1	13169	24
Electrical system	13626	568	2	1	13648	22
Electrical system	14286	596	2	1	14316	30
Electrical system	15461	645	2	1	15540	79
Electrical system	19494	813	3	1	19530	36
Hydraulic System	20112	838	3	1	20149	37
Electrical system	20540	856	3	1	20562	22
Support-Housing	22477	937	3	1	22506	29
Yaw System	23709	988	3	1	23771	62
Yaw System	23921	997	3	1	23941	20
Electrical system	24064	1003	3	1	24113	49
Yaw System	24415	1018	3	1	24447	32
Electrical system	24466	1020	3	1	24807	341
Electronic cont.	24924	1039	3	1	25260	336
Sensors	25789	1075	3	1	25836	47
Electronic cont.	25839	1077	3	1	25860	21
Rotor Blades	29185	1217	4	1	29226	41
Rotor Hub	29835	1244	4	1	29869	34
Sensors	31282	1304	4	1	31315	33
Electrical system	31327	1306	4	1	31362	35
Electrical system	31802	1326	4	1	31842	40
Gearbox	32592	1358	4	2	36448	3856
Electrical system	38276	1595	5	1	38296	20
Sensors	38929	1623	5	1	38970	41
Generator	39817	1660	5	1	39857	40
Sensors	39881	1662	5	1	39900	19
Electrical system	40141	1673	5	1	40167	26
Support-Housing	40834	1702	5	1	41009	175

5.3.4 Power calculation block

Figure 118 shows the simulation phase, which is explained in the section. In order to demonstrate a clear framework, the box associated with this section is highlighted and other boxes are made transparent. The information in Table 33 is also utilised in the power calculation block. In this context, an array, which the size of this array is equal to the number of simulation time steps ($5 * 8760 = 43{,}800$), is created for each turbine considered. Initially, these arrays can only contain the value '1'. Then, the time steps, which the turbines are in failed condition, are identified from datasets similar to Table 33. The '1's in these downtime time steps are changed with '0's in each array. A visual presentation of how these arrays are expressed can be seen in Figure 119. In this figure, '1' denotes uptime and '0' denotes downtime. Although, the uptime period visually appears to be a continuous line, it is actually separated by failures. In this respect, the values and periods in Figure 119 are specifically referring to information provided in Table 33. Due to variability of downtime and uptime periods, each turbine has a unique 'uptime-downtime' array.

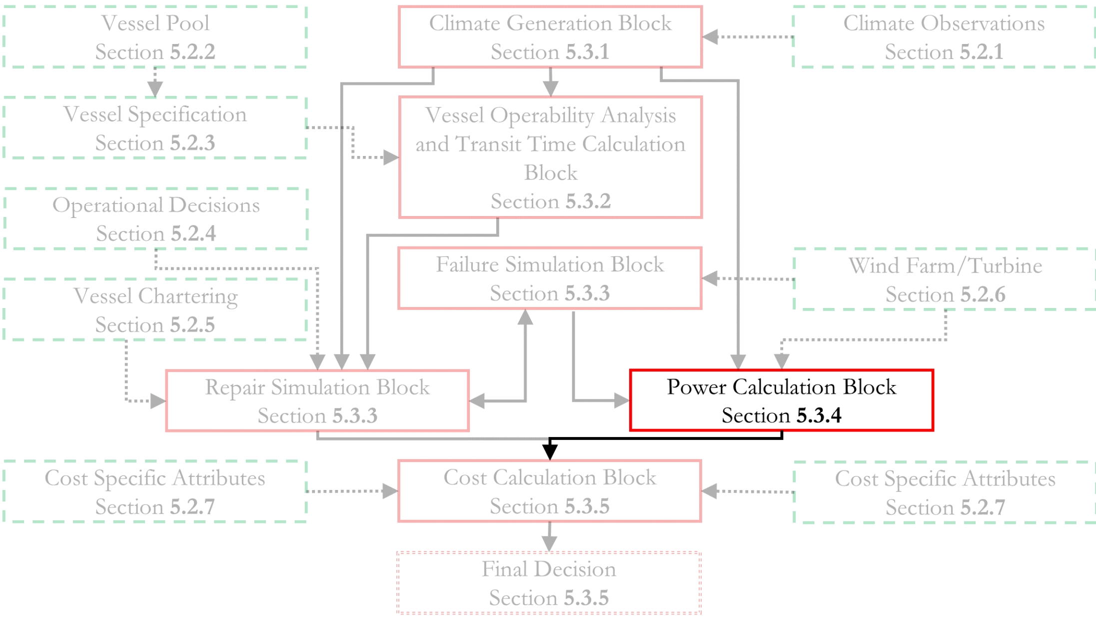

Figure 118: Definition of simulation phase

Thereafter, a 'power production' array, which consists of power production values for a period of 1 hour, is created by considering the turbine power curve (or power production values associated with wind speed values) and the artificial wind speed values at nacelle level. This array is common for all the turbines in the wind farm, and shows the power production without any downtime. The wake effects are neglected in power production calculations. Monthly, seasonal, annual and total power production values can be calculated by considering the values in associated periods. The 'uptime-downtime' arrays are then elementally multiplied by the 'power production' array. Due to the fact that the downtime periods are represented by '0', the multiplication of a power value in downtime period results in '0' power production. This multiplication procedure is repeated for each turbine in a simulation. The total power production of the wind farm can be calculated by summing up all the turbine power production values within simulation period (5 years).

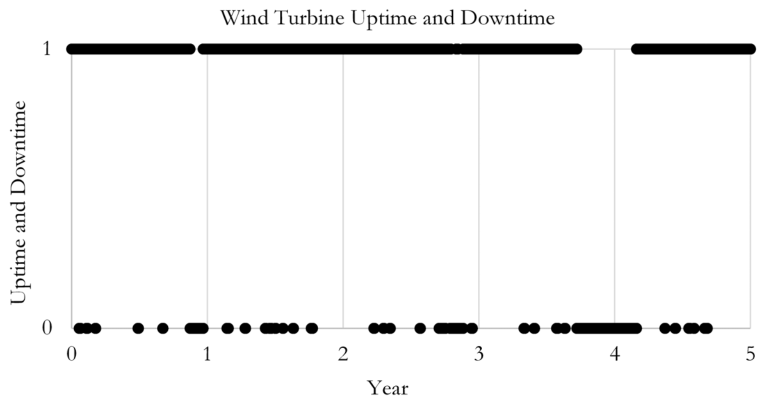

Figure 119: Wind turbine uptime and downtime

5.3.5 Cost calculation block and other simulation results

Figure 120 shows the simulation phase, which is explained in the section. In order to demonstrate a clear framework, the box associated with this section is highlighted and other boxes are made transparent. In this case study, 7614 different O&M fleet configurations, including different CTV types and different chartering alternatives for the jack-up vessel, are simulated. In the following sections, the results of these configurations are presented and key outputs are demonstrated and discussed. The cost calculation formulations are provided in the methodology section of the thesis; therefore, they are not explained again. The costs are presented in the associated sections.

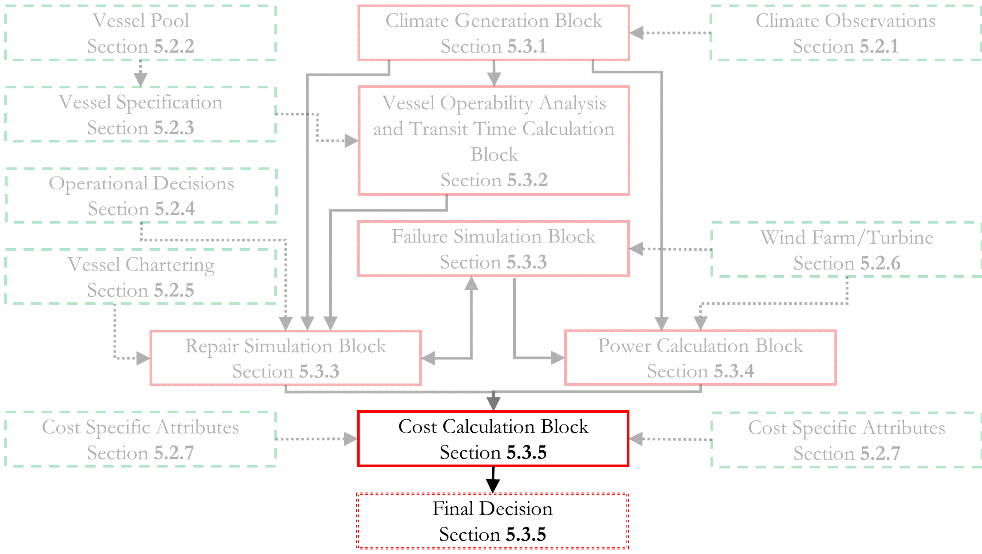

Figure 120: Definition of simulation phase

5.3.5.1 Jack-up vessel results

Due to the fact that the aspects associated with jack-up vessel vary depending on the charter type, the jack-up vessel results are demonstrated separately for long-term charter and short-term charter. In this respect, Figure 121 shows the fuel cost distribution of the jack-up vessel for long-term charter alternative. The number of long-term charter configurations is 282 out of 7614 and these configurations are sorted in a way that the O&M cost/MWh increases by the increase in the configuration number. The 'fuel cost in operation' is always higher than the 'fuel cost in port'; in which the fuel consumption rates play a key role in this difference.

In the majority of the configurations, the total fuel cost and the 'fuel cost in operations' remains above £9M and £7M within the simulation period (5 years), respectively; however, these aspects decline after the wind farm availability drops below 80%. The 'fuel cost in port' remains around £2M. The relation between the jack-up vessel fuel cost and the wind farm availability is not a direct relation. The reason of the wind farm availability decrease is the change in the CTV fleet and the change in the CTV fleet accessibility. The change in the CTV fleet decreases the CTV accessibility; thus, the CTV related failures cannot be attended by the O&M technicians in an efficient way and the turbines remain failed. In this case, the major failures and the jack-up vessel usage is indirectly affected by keeping the turbines in failed condition. Therefore, it should be highlighted that the jack-up vessel fuel cost is indirectly affected by the CTV operations and the reduction in jack-up vessel fuel cost does not always lead to an operational benefit.

Figure 122 presents the distribution of the total jack-up vessel costs in the long-term charter alternative within the simulation period (5 years). The charter, dry-dock, crew, technician, management, and fixed costs are identical for the 282 configurations and the fuel cost is the only aspect changing and thus, it is averaged out. Since the jack-up vessel chartered for long-term and it is always available, there is no penalty considered for the charter cost. On average, the charter cost accounts for 77.5% of the total jack-up vessel costs. The fuel cost has the second highest proportion by slightly above 10%. The remaining 12.5% is shared by dry-dock, crew technician, management, and fixed costs.

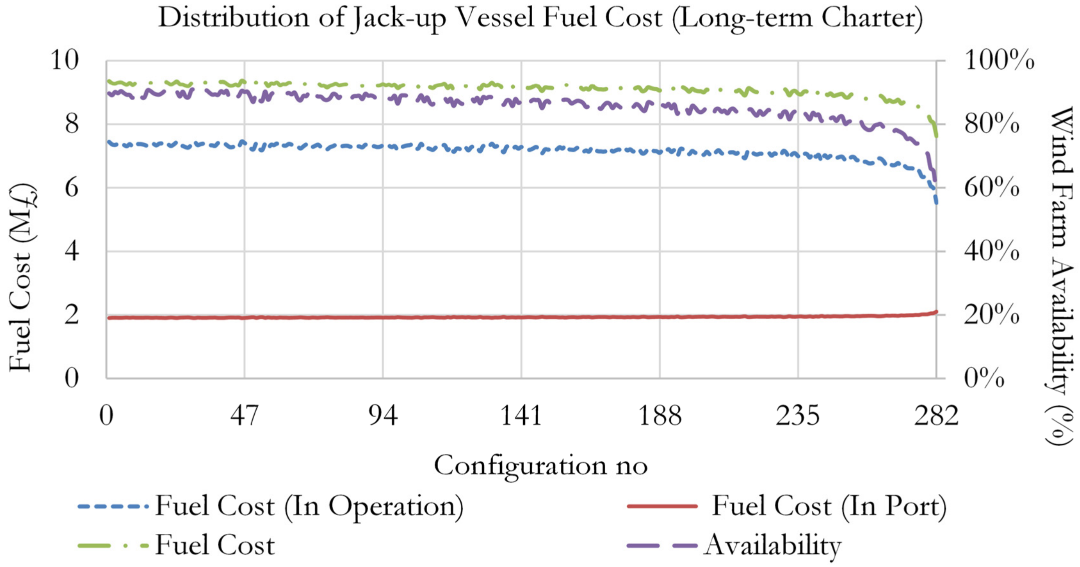

Figure 121: Distribution of jack-up vessel fuel cost (long-term charter)

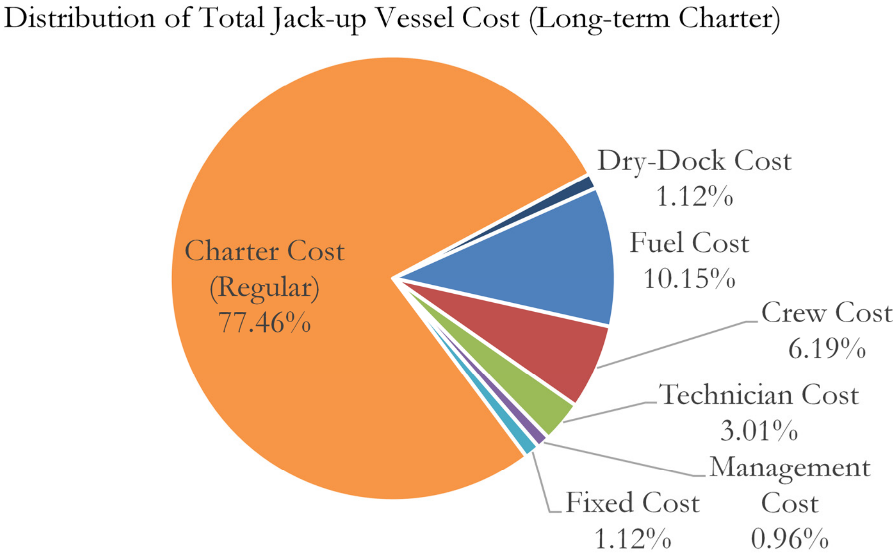

Figure 122: Distribution of total jack-up vessel cost under long-term charter within the simulation period (5 years)

Figure 123 shows the distribution of the total jack-up vessel costs in the short-term charter alternative. In this case, the total jack-up vessel cost comprises of mobilisation, regular charter and penalty charter costs. Due to the change in the charter period (from 1 week to 26 weeks), there is a large variability in the charter costs (both regular and penalty). It should be highlighted that the short-term jack-up vessel charter rates are selected from the spot market charter rates. Therefore, there is no particular change in the daily charter rate with respect to increase in the charter period. The change in the total charter cost is due to the change in the equilibrium of regular and penalty payments. Considering the limited data availability, it would not be practical to allocate different spot market charter rates to different short-term charter periods. The mobilisation cost is expected to be around £5M for the entire simulation period (5 years). The total jack-up vessel charter cost varies between £40M and £90M, which is elaborated in the following figure. Figure 124 demonstrates the change in the jack-up vessel costs with respect to the change in the charter period. In this example, the most favourable CTV fleet is identified and the costs associated with 26 different (from 1 week to 26 weeks) jack-up vessel charter periods are demonstrated. By keeping the CTV fleet fixed, the influence of the charter period on the jack-up vessel costs can clearly be noticed.

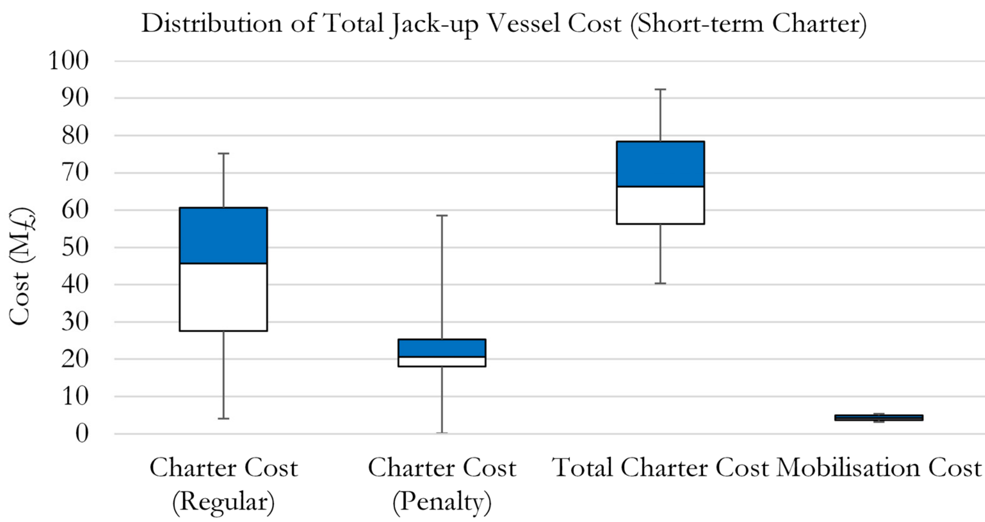

Figure 123: Distribution of total jack-up vessel cost (short-term charter)

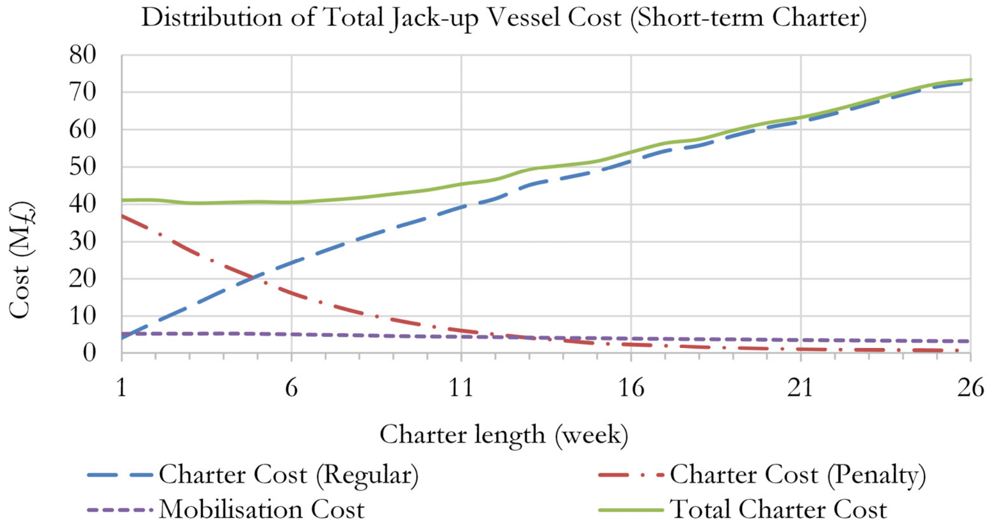

Figure 124: Distribution of total jack-up vessel cost (the most favourable CTV fleet)

Essentially, there is an inverse proportion between the regular and penalty charter costs. The regular charter cost increases by the increase in the charter period; on the contrary, the penalty charter cost decreases. This gives the total jack-up vessel charter cost a 'U' shape. In this respect, there is an optimal point that the total jack-up vessel charter cost is minimised, in which, the regular and penalty charter cost curves cross. The penalty charter cost is about £40M and decreases gradually by the increase in the charter period. This is because, the jack-up vessel can attend a large number of failures in the regular charter period; so the penalty is minimised. Although the penalty charter cost decreases towards £0, there is no particular limit for the regular charter cost; it increases proportional to the increase in the jack-up vessel charter period. Therefore, chartering the jack-up vessel for longer periods can minimise the penalty charges; however, this can also lead to unnecessary regular payments, which increases the costs without achieving any operational benefit.

The operational benefits can be elaborated by investigating the jack-up vessel utilisation for each chartering alternative. In this respect, Figure 125 presents the jack-up vessel utilisation for long-term charter and short-term charter. Since the vessel is charted for 5 years, the utilisation is lower for the long-term charter than the utilisation for short-term charter. When the utilisation values for short-term charter are taken into account, it can be seen the utilisation drops by the increase in the charter period. When the average utilisation is above 95% when the jack-up vessel is charted for a week; it drops below 65% when the jack-up vessel charter for 12 weeks (3 months). Since utilisation is the proportion of the time steps that the vessel is utilised to the total number of time steps in the charter period, it is expected that the utilisation decreases by the increase in the charter period. At this stage, it is important to highlight the fact that jack-up vessel utilisation has no direct influence on the financial aspects; however, it shows how efficiently the jack-up vessel is utilised. In this respect, it is important to indicate that very high utilisation can be achieved by chartering the jack-up vessel for shorter terms; however, in this case, penalty charges can be excessive. Therefore, the balance between utilisation and charter payments are significantly important.

From the mobilisation cost point of view, the increase in the charter period has a positive effect. This is mainly due to the number of failures that can be repaired in a single charter period. Considering the fact that the number of failures increases by time, the number of failures that can be attended by chartering the vessel for longer terms increase; therefore, the number of vessel charters decrease by chartering the vessel longer. As a basic logic, if one failure occurs every week and if the jack-up vessel is chartered for a week, four mobilisation operations need to be performed in a month. On the other hand, if the vessel is charted for four weeks, the mobilisation is paid only once in the same period of time. In this case, the cost of mobilisation can result in a minor change in the total jack-up vessel cost; however, the mobilisation time (lead time) also needs to be taken into account.

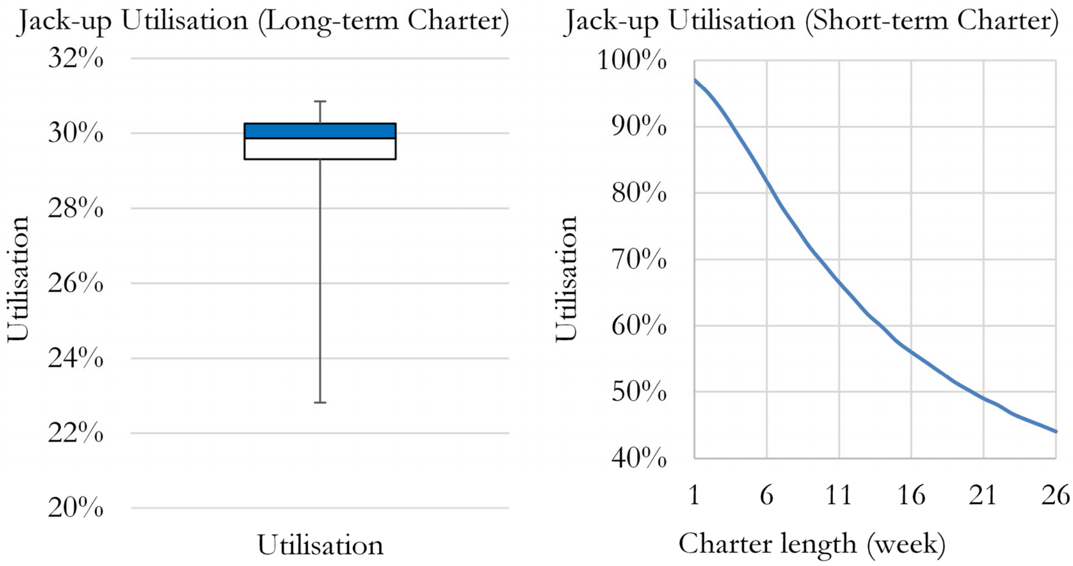

Figure 125: Jack-up vessel utilisation

5.3.5.2 CTV results

In this section, the CTV associated outputs are presented. Figure 126-Figure 128 are the graphical illustrations of how the total O&M cost responses to the change in the associated CTV within the entire CTV fleet. The red dashed vertical lines in these figures separate the fleet configurations, which only comprise of this particular CTV type and the fleet configurations, which do not include any of this particular CTV type. For instance, the left hand side of the red dashed line in Figure 126 shows the fleet configurations only with the 26 m WFSV, so there is no any 21 m or 17 m WFSV in these configurations. On the other hand, the right hand side of the red dashed line in Figure 126 shows the configurations without the 26 m WFSV. The same approach is implemented to create Figure 127 and Figure 128. By separating the configurations for each CTV type, it is intended to demonstrate the absolute advantage or disadvantage. In Figure 126, the configurations with 26 m WFSV has a clear financial benefit compared to the configurations without 26 m WFSV. The total O&M/MWh exceeds £45/MWh, when there is no 26 m WFSV in the CTV fleet. On the other hand, the configurations, in which the 26 m WFSV is considered, lead to total O&M costs below £40/MWh. The variability in the left hand side of the red dashed line is due to the change in the jack-up vessel charter period, while the variability in the right hand side of the red dashed line is due the change in the jack-up vessel charter period and the CTV fleet composition.

When the separations in Figure 127 and Figure 128 are examined, it can be seen that the configurations, in which these CTV types are considered in the CTV fleet, do not bring a financial advantage. The total O&M cost does not drop below £46/MWh or £60/MWh if the CTV fleet is comprised of only 21 m WFSV or 17 m WFSV, respectively. The majority of the configurations without 21 m WFSV are more favourable than the configurations with 21 m WFSV. Furthermore, almost all the configurations without 17 m WFSV lead to a lower total O&M cost/MWh than the configurations with 17 m WFSV.

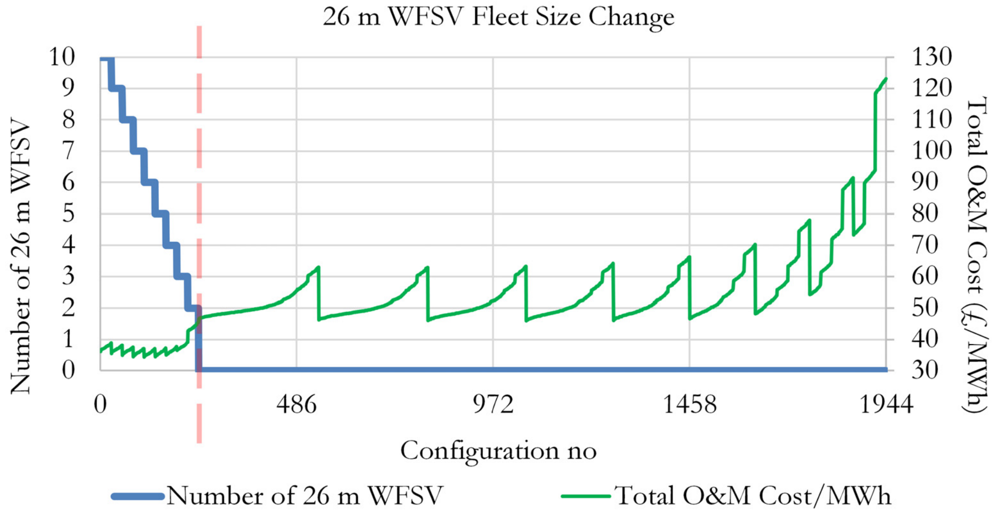

Figure 126: The influence of 26 m WFSV on the total O&M cost/MWh

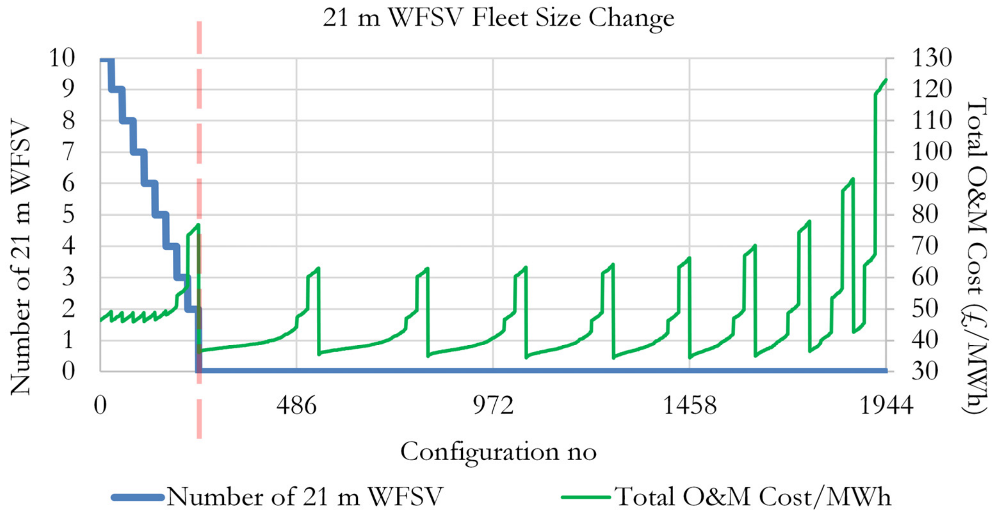

Figure 127: The influence of 21 m WFSV on the total O&M cost/MWh

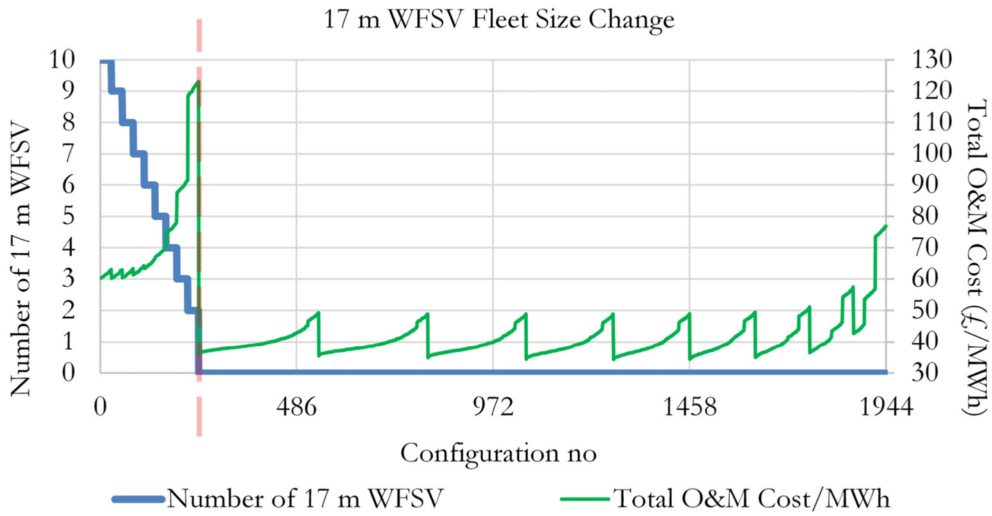

Figure 128: The influence of 17 m WFSV on the total O&M cost/MWh

In addition to the results associated with each CTV type, Figure 129 shows the change in the total O&M/MWh with respect to the change in the entire CTV fleet. At the beginning of the case study, the maximum and the minimum size of the CTV fleet are defined as 10 and 2, respectively. The key output of this figure is that the identification of the CTV fleet size is not sufficient in order to minimise the costs. It can be seen that the total O&M cost/MWh varies within each fleet size. For instance, when the CTV fleet comprises of 10 CTVs as in the left side of Figure 129, the total O&M cost/MWh fits in a range of £37/MWh-£63/MWh. This is a significantly large variability, which can move a cost effective project to a high priced project. The influence of the CTV fleet size becomes dominant for the smaller CTV fleets. In this particular case study, if the CTV fleet comprises of 3 (or less) CTVs, the failures remains attended for longer periods. Although, the total O&M cost decreases by considering a smaller fleet, the total O&M cost/MWh increases substantially. This is because, the power production cannot be sustained anymore. For smaller fleets, the cost variability becomes key factor; defining the fleet composition in a wrong way can increase the total O&M cost/MWH from £42/MWh to £123/MWh.

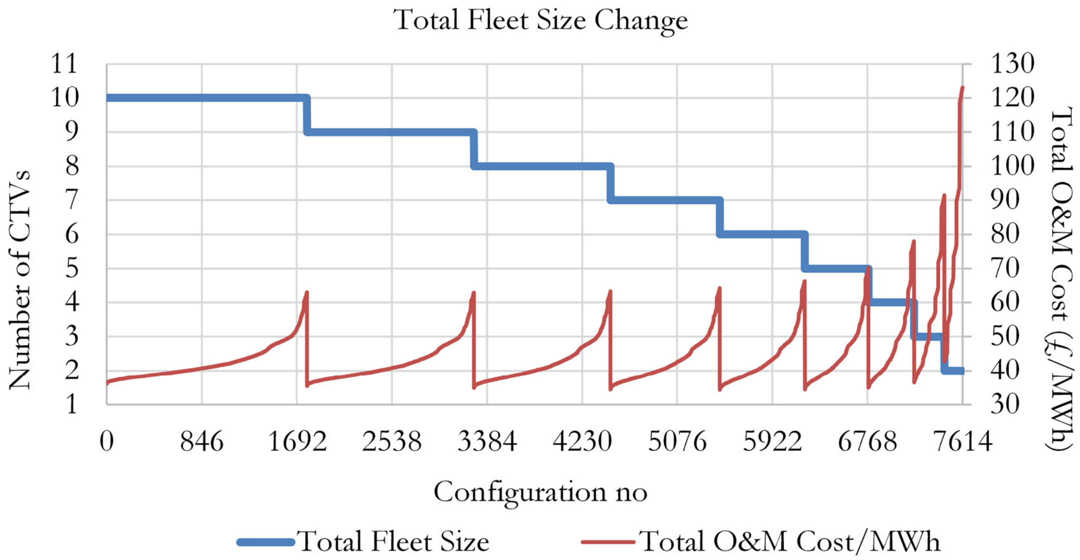

Figure 129: The influence of CTV fleet size change on the total O&M cost/MWh

Figure 130-Figure 132 demonstrate the distribution of CTV fleet for each CTV type. The markers in these figures show the proportion of that particular CTV type to the entire fleet size. By sorting these configurations with respect to increasing total O&M cost/MWh, the change in the fleet compositions can be understood in depth. The red dashed rectangles in these figures indicate the areas with high and low total O&M

cost/MWh and also point out the key difference in the distribution of the fleets. In Figure 130, it can be seen that the CTV fleets, which lead to a low O&M cost/MWh, generally consist of 26 m WFSV with large proportion (50% or more). The fleet compositions with lower number of 26 m WFSVs results in higher total O&M cost/MWh as in the right side of this figure. Figure 131 and Figure 132 have the opposite trends compared to Figure 130. The compositions, in which the proportion of 21 m WFSVs and 17 m WFSVs is high (50% or more), results in high total O&M cost/MWh. The highest total O&M cost/MWh is occurred when the CTV fleet is composed of two 17 m WFSVs. The main aspect, which makes the 26 m WFSV more favourable is the relatively high level of absolute accessibility compared to other CTV types. Although 21 m WFSV is faster and 17 m WFSV is cheaper to operate, the key results discussed in the CTV section show that the 26 m WFSV brings a strong advantage to the O&M activities. Furthermore, the results also show that the consequences of an inaccurate decision in the O&M planning stage can be excessive.

Figure 133 shows the distribution of total CTV fuel and staff costs. The total CTV fuel cost comprises of internal and external (port-site) fuel costs. The total CTV staff cost comprises of crew and technician costs. The cost of external transfers is more than the cost of internal transfers. Essentially, the time spent on external travels are more than the time spent on wind farm internal travels. On average, the ratio of the internal travels to the external travels is 0.61. The maximum travel values observed in the simulations are 3219 hours (26 m WFSV), 2320 hours (21 m WFSV) and 1791 hours (17 m WFSV) during external travels and 2386 hours (26 m WFSV), 1913 hours (21 m WFSV) and 1371 hours (17 m WFSV) during internal travels. The reason for the cost difference among different CTV types is the variability in the CTV accessibility to the turbines. Due to the fact that 26 m WFSV has the highest accessibility, this CTV is utilised more frequently and therefore, travelled more than other CTV types. When the comparison is made from staff cost point of view, the cost of technicians has a larger proportion in the total staff cost than the cost of crew, even though the average salary of crew members is higher. This is due to the difference in numbers associated with each CTV (2 crew members and 12 technicians per CTV).

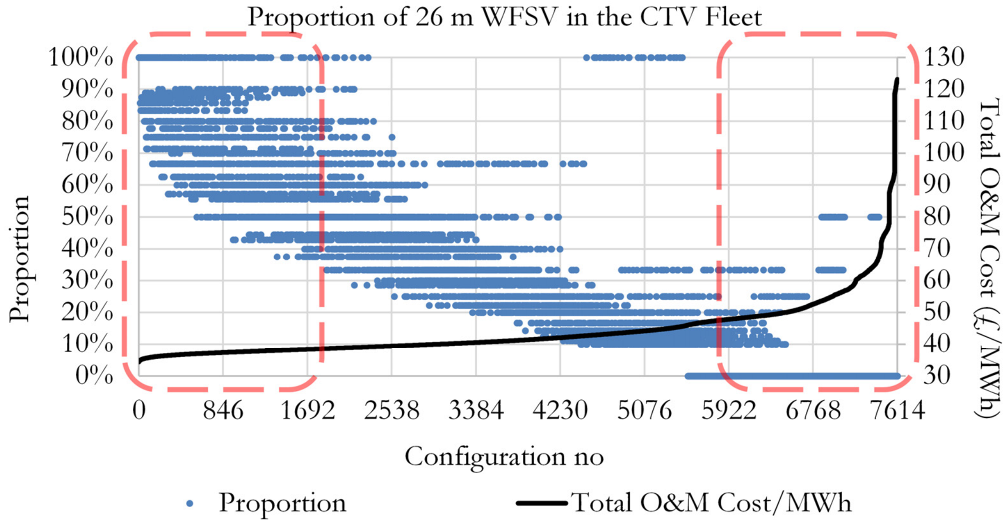

Figure 130: The proportion of 26 m WFSV in the entire CTV fleet

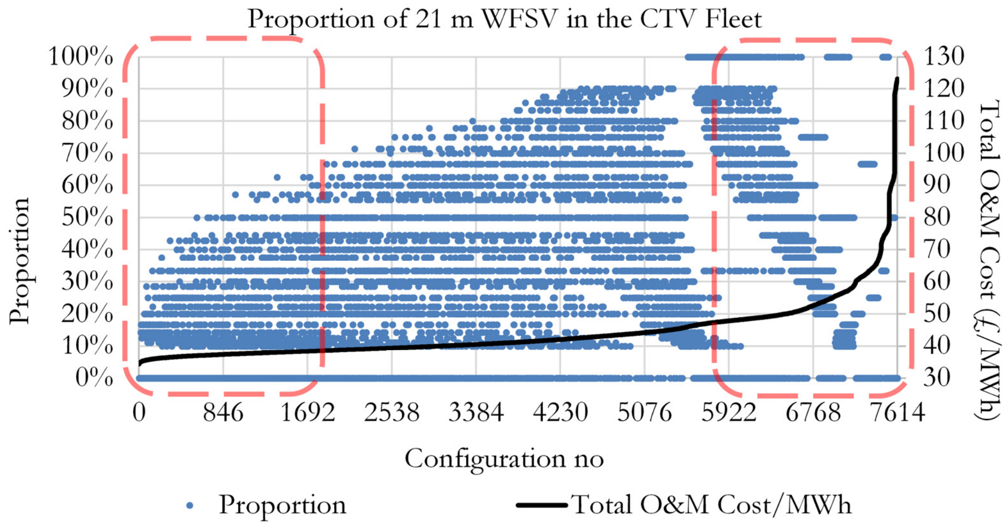

Figure 131: The proportion of 21 m WFSV in the entire CTV fleet

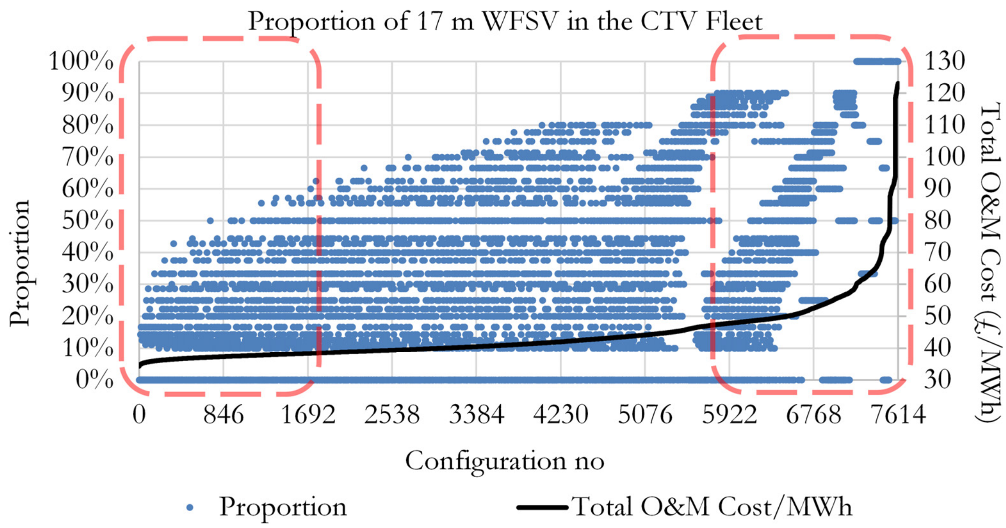

Figure 132: The proportion of 17 m WFSV in the entire CTV fleet

In addition to these two CTV cost aspects, Figure 134 demonstrates the distribution of overall CTV costs. It can be noticed that CTV charter cost and CTV staff costs have the highest two proportions within the overall CTV costs; however, a large variability can also be noticed. This is because, CTV associated costs are significantly related to the CTV fleet size. In the case study, the size of CTV fleet varies between 2 and 10. The charter cost of a CTV fleet with 2 vessels can cost less than £10M in 5 years, while the charter cost of a CTV fleet with 10 vessels can cost more than £60M. In order to make a reasonable comparison, CTV associated costs are normalised in accordance with the size of the CTV fleet. As a result, the variability is decreased as shown in Figure 135. In this case, the fuel cost, staff cost, fixed cost, charter cost account for 3%, 42%, 3%, and 52%, respectively. For the most favourable CTV fleet, the contribution of these aspects are 4%, 35%, 2%, 59%, respectively; in which the contribution of staff cost converges to minimum value; on the other hand the contribution of charter cost converges to maximum value.

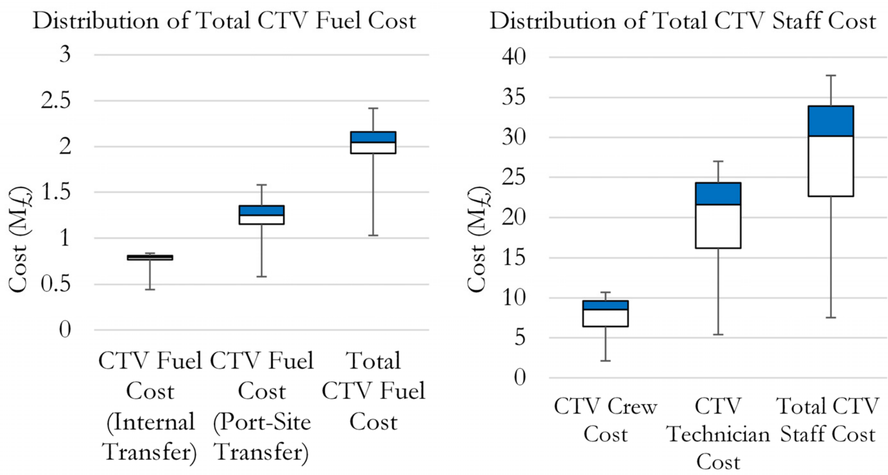

Figure 133: Distribution of CTV fuel and staff costs

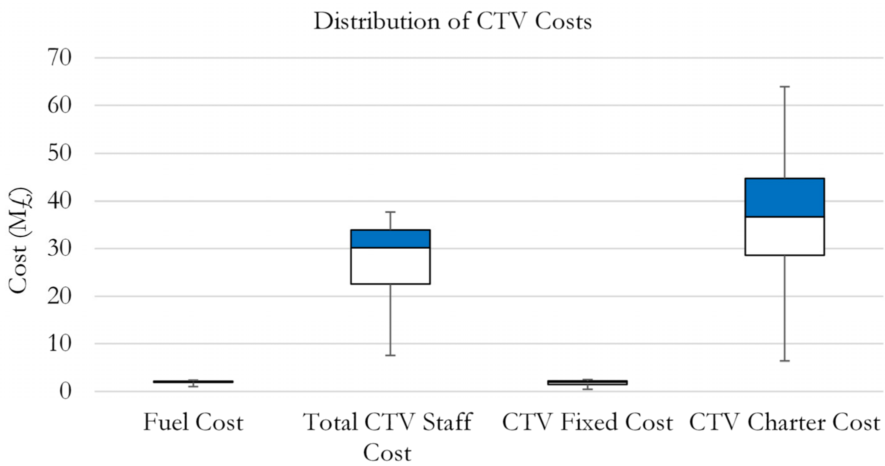

Figure 134: Distribution of CTV costs

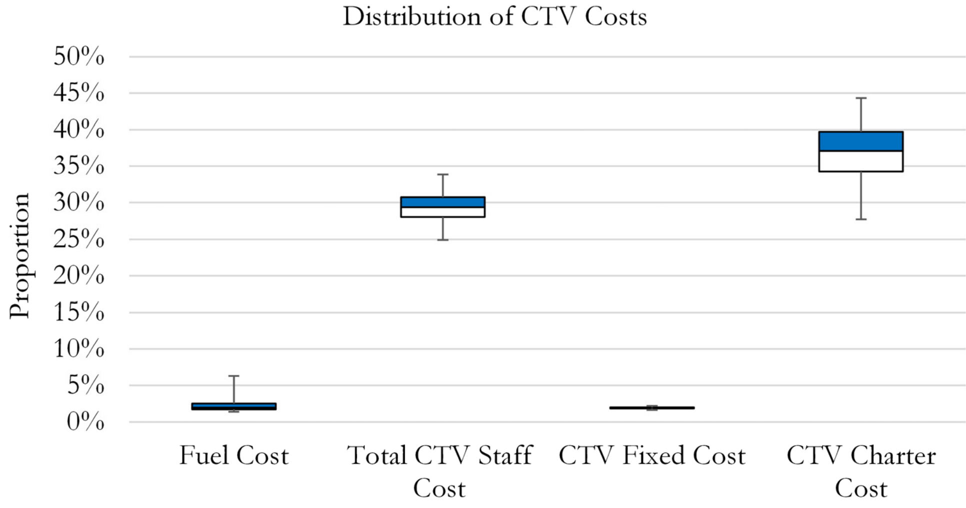

Figure 135: Distribution of CTV costs (proportional to the fleet size)

Table 34 shows the average operational results of the CTVs. It can be seen there is a significant difference between the accessibility values. The accessibility can be increased from 32% to 59% by using the 26 m WFSV instead of the 17 m WFSV in the O&M fleet. The 'idle time', 'productive time' and 'travel time' values in this table are applicable, when the wind farm is accessible by a CTV. The 'productive time' is higher and the 'idle time' is lower for the 26 m WFSV, which means that the 12-hour working shift can be used in a more efficient way with the 26 m WFSV. Its operational limits allow the 26 m WFSV to travel in harsher conditions, so, the productive period can be maximised. The 21 m WFSV has the lowest travel time, because its operational speed is higher than the other CTVs in the fleet.

Considering the number of technicians allocated and the number of turbines visited in a repair day, it can be noticed that the technicians allocated and the turbines visited increase by the decrease in the accessibility. This is because lower accessibility results in an increase in the number of failures, which needs to be visited in a repair day. Therefore, high number of failed turbines requires high number of visits by the CTVs, which transport high number of O&M technicians on-board.

Table 34: CTV average operational results

	26 m WFSV	21 m WFSV	17 m WFSV
Accessibility	0.59	0.47	0.32
Idle Time (h)	2.01	2.39	2.43
Productive Time (h)	6.94	6.88	6.50
Travel Time (h)	3.03	2.72	3.05
Technicians allocated	6.55	6.72	8.06
Turbines visited	2.46	2.71	3.08

5.3.5.3 Power production, availability and MTTR results

In this section, the results associated with the aspects that influence the power production are presented. Figure 136 shows the distribution of MTTR values; the failure modes in this graph refer to the component names in Table 25. A significant difference can be observed between the minor failure MTTR values (1-12) and major failure MTTR values (13-16). A large variability is also noticed in all failure modes. In order to elaborate and identify the key aspect that causes the large variability, the MTTR values are separated under the long-term and short-term jack-up vessel chartering strategies. In Figure 137, the MTTR values are demonstrated by considering the alternative jack-up vessel chartering strategies. The assessment of these graphs show that the long-term jack-up vessel charter leads to the minimisation of the major failure MTTR values; however, it does not have any influence on the minor failure MTTR values. The MTTR values for long-term jack-up vessel charter vary between 500 hours and 700 hours depending on the failure mode; on the contrary, the MTTR values for short-term jack-up vessel charter vary between 1,500 hours and 2,700 hours. In this respect, these MTTR values are sorted with respect to increasing jack-up vessel charter period (the graph at the bottom). It can be noticed that the highest MTTR values are observed when the jack-up vessel is chartered for shorter terms. This is because, the longer charter maximises the number of turbines that can be maintained in a single charter agreement.

Figure 138 shows the influence of CTV fleet composition on the MTTR values. The MTTR values in these graphs are the average of the minor failure MTTR values. As shown in Figure 137, the minor failure MTTR values vary between 80 hours and 660 hours depending on the fleet configuration. Decreasing number of the 26 m WFSV within the CTV fleet leads to an increase in the MTTR values. The lowest MTTR values are observed, when the CTV fleet consist of 10 26 m WFSVs. On the contrary, the largest MTTR values are observed, when the CTV fleet consists of 2 17 m WFSVs.

If all the MTTR values (both minor and major failures) are taken into account, it can clearly be noticed that there is a strong relation between the MTTR values and the accessibility & availability of the vessels in the O&M fleet. Chartering the jack-up vessel for longer periods decreases the number of vessel charters within the simulation period (5 years). Considering the fact that mobilisation significantly delays the jack-up vessel operations, minimising the number of jack-up vessel charters is the key to minimise the total mobilisation time and eventually MTTR values. Chartering the jack-up vessel for the entire simulation period maximises the vessel availability and eliminates the mobilisation period. From CTV operations point of view, CTVs with higher accessibility can lead to lower MTTR values. A larger CTV fleet is also important to decrease the MTTR values; because the reaction time to failures can be reduced. However, CTV accessibility is a more important aspect than the size of the fleet.

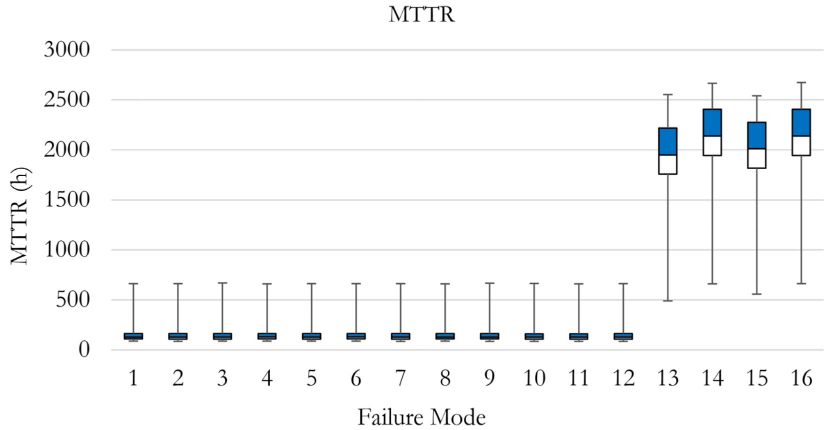

Figure 136: MTTR values

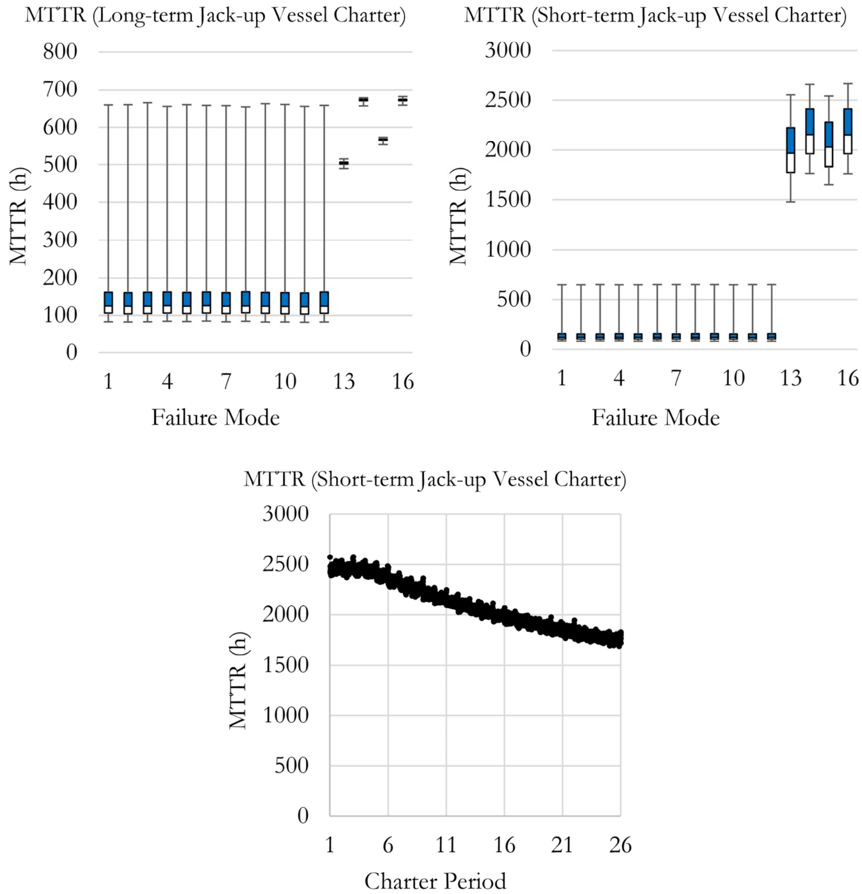

Figure 137: MTTR values relative to jack-up vessel charter

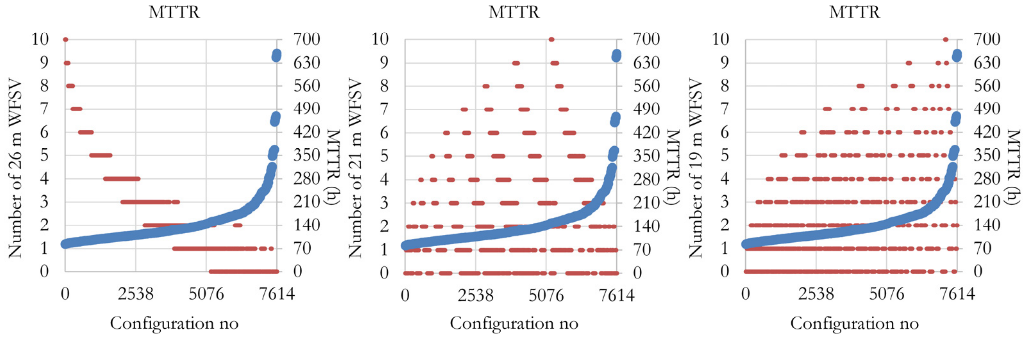

Figure 138: MTTR values relative to CTV configuration

Figure 139 shows the total power production, availability and capacity factor values observed in the simulations. An accurate decision can lead to an increase in the power production, wind farm availability and capacity factor, on the other hand, a wrong decision can lead to significantly low power production, availably and capacity factor. The wind farm in the case study has the potential to produce 10.8 10^6 MWh power within 5 years. This can be achieved by an average 90% availability and so, 49% of the total capacity is used. On the other hand, if the O&M fleet configuration is not planned well enough, the wind farm can only produce 6.8 10^6 MWh power within 5 years, which is 37% less compared to the wind farm's potential. In this case, the availability drops to 57% and only 30% of the total capacity is used. The critical aspect at this stage is the fact that the availability is the intermediate output, but the final (major) output is the capacity factor and total power production.

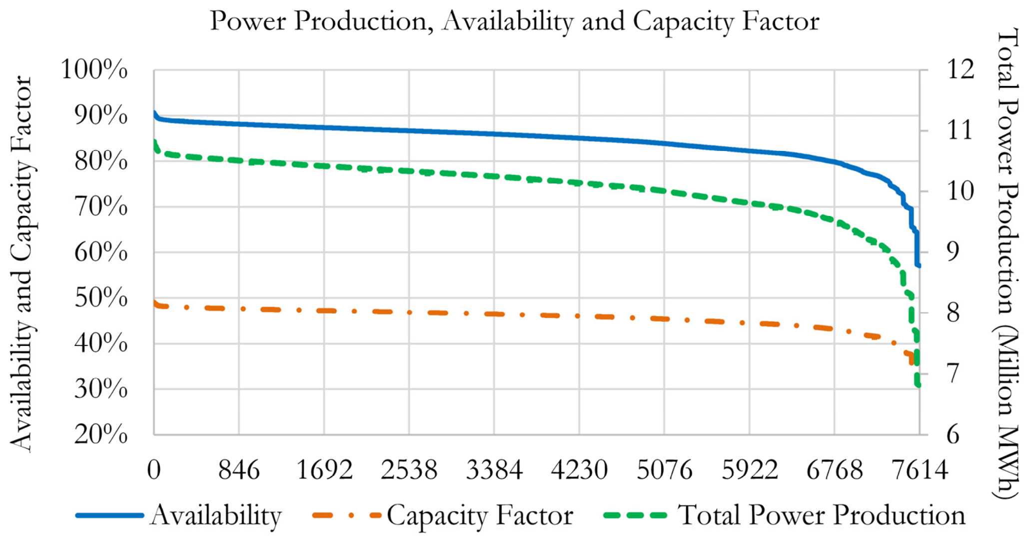

Figure 139: Variability in total power production, availability and capacity factor

5.3.5.4 Cost results and final decision

In the previous sections, the results of the simulations are mainly evaluated from operational benefits point of view. In this section, the results are interpreted from cost point of view. For the final decision, the configurations are then compared according to their total O&M cost/MWh values, which consists of direct O&M cost and revenue loss due to loss in power production. Total O&M cost/MWh is selected for the final comparison, because it reflects the level of financial benefit (production increase) and loss (cost increase) achieved through considering the most favourable O&M fleet. Figure 140 demonstrates the change in the total O&M cost and revenue loss. In the best configuration, the total O&M cost is £34.32/MWh and the revenue loss is 21.96%. In the worst configuration, the total O&M cost is £123.18/MWh and the total revenue loss is 50.19%. The other configurations fit in between these values.

In order to provide a more clear comparison the best and the worst ten configurations are presented in Table 35 and Table 36. The values separated by dash in the 'CTV Fleet Configuration' column are the number of 26 m, 21 m and 17 m WFSVs in the O&M fleet, respectively. In the best configuration, the jack-up vessel is chartered for five weeks and six '26 m WFSVs' are considered in the CTV fleet. In the worst configuration, the jack-up vessel is charted for 26 weeks and two '17 m WFSVs' are considered in the CTV fleet. Despite its higher daily charter rate, 26 m WFSV is identified as a more cost effective CTV than the other CTVs. On the contrary, 17 m WFSV leads to a significant cost increase, even though the daily charter rate is half of the '26 m WFSV'. Short-term jack-up vessel charter is observed in the best and in the worst scenarios; however, the length of charter is altered. Five weeks charter is identified as the most favourable jack-up charter period; on the other hand, 26 weeks charter is identified as the least favourable jack-up charter period. This is because, when the jack-up vessel is charted for a period longer than the optimum, its utilisation drops. In this case, the total charter cost increases, however, the power production increase is not enough to compensate this cost increase.

It can also be noticed that the availability is not the highest availability observed in the simulations. In Figure 139, it is shown that 90% availability can be achieved; however, the jack-up vessel needs to be chartered for long-term, which increases the jack-up vessel charter cost. Therefore, it is important to evaluate the power production and O&M costs at the same time; because, they have an interaction.

The summation of the revenue loss due to decrease in power production and total O&M cost is equal to £359M within 5 years for the most favourable configuration. In order to present the financial benefit in a more clear way, the values of revenue loss and O&M cost are presented relative to the best configuration. For instance, the financial loss for the worst configuration is £838.41M (£479.41M+£359M). It can be noticed that, the financial loss increases with respect to change in the configuration. The difference between the best and the worst configuration is more than 230%, which clearly shows how much an inaccurate decision can cost to an operator within a period of 5-years.

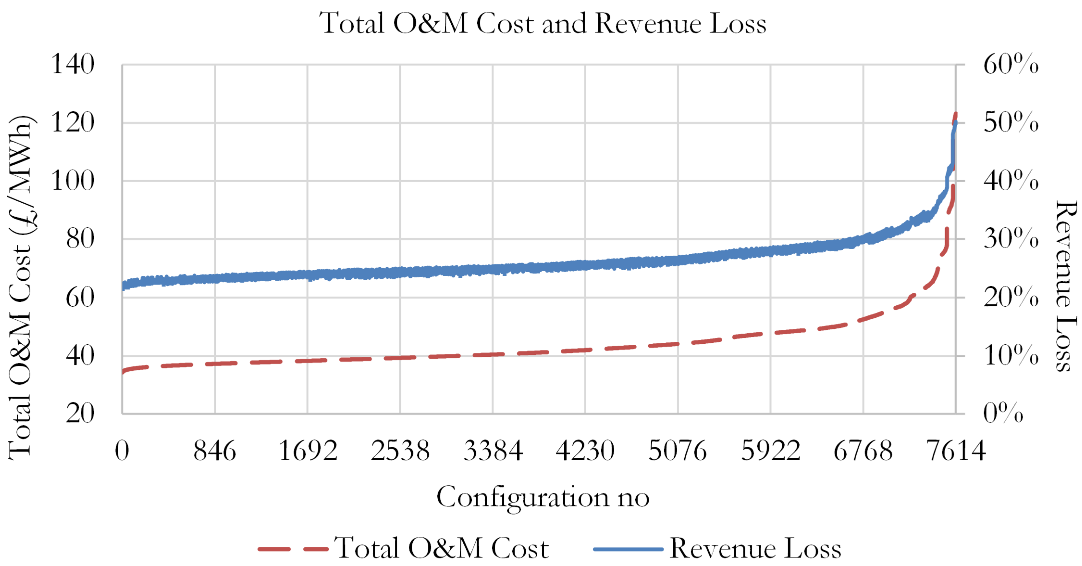

Figure 140: Total O&M cost and revenue loss

Table 35: Best 10 configurations

No	Total O&M Cost (£/MWh)	Availability (%)	Jack-up Vessel Charter Type	Jack-up Vessel Charter Period	CTV Fleet Configuration	Revenue Loss+ O&M Cost
1	34.327	87.6	Short-term	5 weeks	6-0-0	£359M
2	34.453	87.1	Short-term	5 weeks	5-0-0	+£1.31M
3	34.454	87.1	Short-term	6 weeks	5-0-0	+£2.59M
4	34.567	87.7	Short-term	6 weeks	6-0-0	+£2.56M
5	34.613	87.7	Short-term	7 weeks	6-0-0	+£3.17M
6	34.691	87.0	Short-term	4 weeks	5-0-0	+£3.39M
7	34.797	87.5	Short-term	4 weeks	6-0-0	+£3.66M
8	34.843	88.0	Short-term	4 weeks	7-0-0	+£3.87M
9	34.852	87.2	Short-term	8 weeks	5-0-0	+£4.00M
10	34.875	87.2	Short-term	7 weeks	5-0-0	+£4.67M

Table 36: Worst 10 configurations

No	Total O&M Cost (£/MWh)	Availability (%)	Jack-up Vessel Charter Type	Jack-up Vessel Charter Period	CTV Fleet Configuration	Revenue Loss+ O&M Cost
1	123.183	57.2	Short-term	26	0-0-2	+£479.41M
2	122.822	57.2	Short-term	25	0-0-2	+£478.97M
3	122.458	57.2	Short-term	24	0-0-2	+£476.76M
4	122.454	57.2	Short-term	23	0-0-2	+£474.59M
5	122.421	57.2	Short-term	22	0-0-2	+£474.58M
6	122.291	57.2	Short-term	21	0-0-2	+£473.08M
7	121.901	57.1	Short-term	20	0-0-2	+£471.12M
8	121.896	57.1	Short-term	19	0-0-2	+£469.30M
9	121.726	57.1	Short-term	18	0-0-2	+£468.07M
10	121.455	57.1	Short-term	17	0-0-2	+£468.02M

In the previous sections, the costs associated with each category are interpreted within the category itself; however, it is more important to make the comparison among these categories in order to identify the key areas, which can lead to highest cost reduction. In this respect, Figure 141 shows the distribution of the total O&M cost and the total direct O&M cost. In the total O&M cost distribution, it can clearly be seen that the revenue loss due to power production loss is the most dominant aspect, which increases the costs. The configurations, in which the availability is significantly low, can result in £700M revenue loss within 5 years. In order to observe the direct O&M cost aspects in a more clear way, these cost categories are demonstrated in a separate graph. Essentially, the values in these two graphs are same, but due to its relatively high value, the revenue loss makes the other cost aspects appear to be smaller and not easy to interpret.

Among the total direct O&M cost aspects, the jack-up vessel has the highest contribution, which is followed by the CTV charter cost and the CTV staff cost. The red points in these graphs show the values, if the most favourable configuration is selected. It can be seen that the most favourable strategy is not the cheapest strategy. On the other hand, it prevents the operators to spend more than the optimal point. In this case, O&M cost can be assumed as an investment, which the return is the power production. There is a certain point that this investment has the optimum return. If this point is exceeded, the return increases; however, the investment that needs to be done is more than the return. Due to the fact that the most favourable strategy requires short-term jack-up vessel chartering, the fuel, staff and fixed costs are expected to be £0. On the other hand, there is a mobilisation cost that needs to be bear in mind.

The total OEM cost is close to its maximum value for the most favourable configuration. This is associated with keeping the turbines maintained and functioning. It should be highlighted that the simulations are not associated with increasing the reliability or decreasing failure rates of the turbine components. The OEM cost reduction in Figure 141 is only about not maintaining the turbines. In this case, the OEM cost can be reduced, but the revenue loss increases significantly.

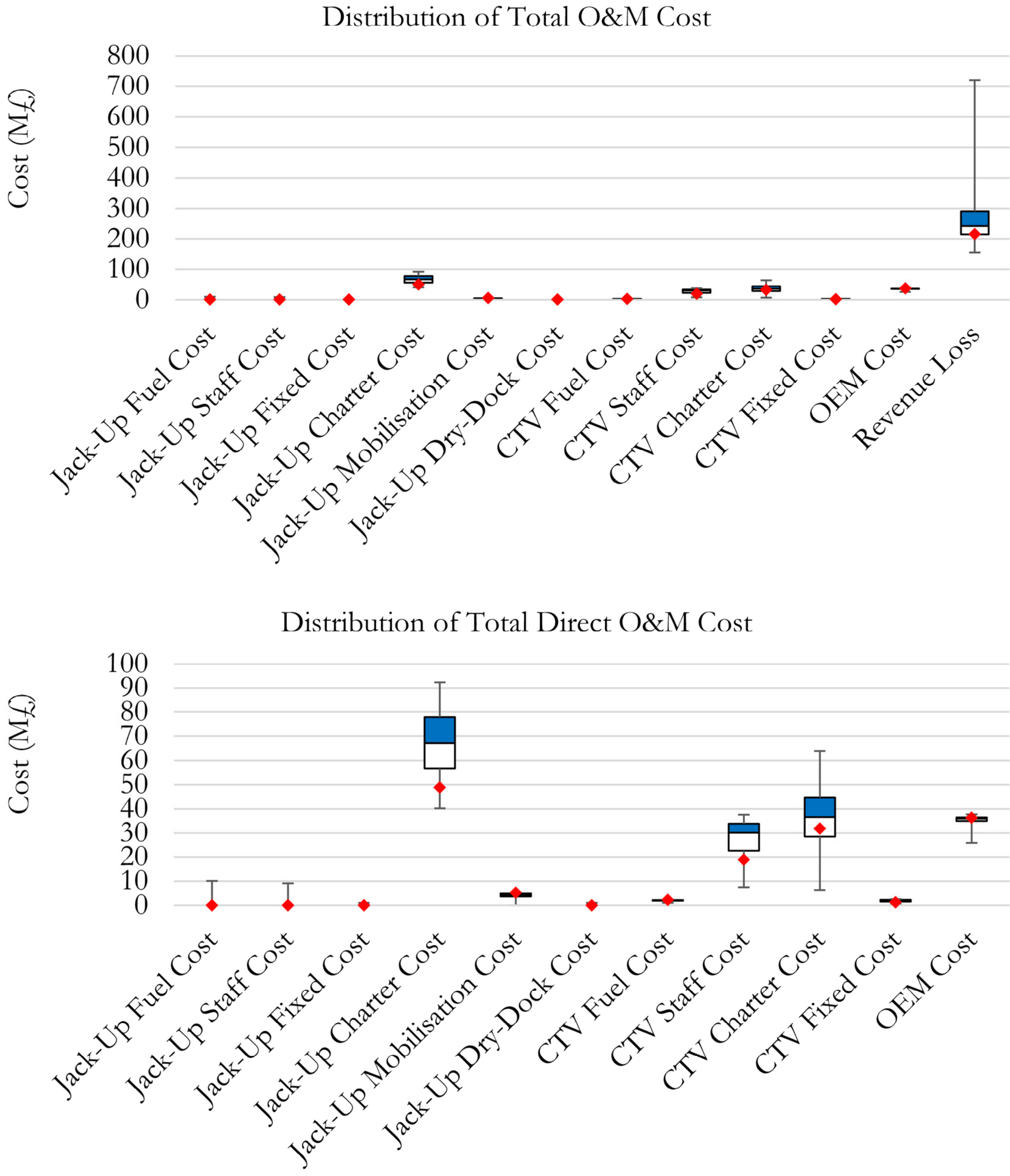

Figure 141: Distribution of total O&M cost and total direct O&M cost

5.4 Chapter summary

In order to preserve the consistency in the thesis, and link the interactions between chapters in a more clear way, the arrangement of this chapter is remained similar to the arrangement of Chapter 4. This case study chapter starts with the presentation of the input sections. These inputs are first defined and then used in the analysis sections, which are all explained in depth. In this chapter, a 3.6 MW 140-turbine wind farm configuration is taken into account, investigated and operational simulations are run. In the O&M vessel pool, 3 different CTV types and their characteristics are considered. The minimum and the maximum CTV fleet size values are defined as '2' and '10', respectively. In addition, a single jack-up vessel, which can be chartered in two different ways (short-term and long-term), is included in the operational simulations. After identifying the input parameters, the analysis/calculation sections: climate generation, vessel operability and transit time calculation, failure simulation, repair simulation, power calculation, cost calculation blocks are described. The key outputs of each section are presented under each category.

In the cost calculation block, how the final decision is made and the most favourable O&M fleet configuration are presented. By demonstrating the best and the worst configurations, the key aspects that lead to high or low O&M costs can be spotted. The distribution of total O&M cost is also provided in the cost calculation block, so, the proportion of the major aspects that contribute to the O&M cost can be assessed. The cost distribution is important, because it shows the key areas, which are critical from financial point of view. The total O&M cost can be optimised by focusing the aspects that have the highest proportion within the overall cost.

In this case study, it is shown that the CTVs with higher operational limits bring an advantage to the offshore wind O&M activities. Although, their daily charter rates are higher than the smaller CTVs, they are crucial to sustain the power production. Five weeks short-term jack-up vessel chartering is identified as the most favourable configuration. Although the MTTR values are higher for short-term charter, long-term charter requires a larger investment, which cannot be compensated. However, long-term jack-up vessel charter can be beneficial for larger wind farms and larger turbines. In the next chapter, a case study about mothership concept is presented in order to demonstrate operational simulations for a far offshore location.

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6 Case Study – Benefits of Mothership Concept

6.1 Chapter outline

In this chapter, a particular focus is given to the 'mothership concept' and its usage within the O&M fleet. Initially, the reasons why operators need to consider a mothership are introduced to the reader. Then, the characteristics of a mothership is presented. A base case, in which a mothership is not considered, is presented and then major scenarios, in which a mothership is considered, are simulated in order to identify the most favourable plan (either long term or short term) that brings maximum financial and operational benefits. At the end of this chapter, the results and discussion about the mothership concept are demonstrated, and the chapter is finalised by the chapter summary.

6.2 Mothership concept

In far offshore, challenging climate conditions limit the operability and the accessibility of the maintenance vessels significantly. Furthermore, if significant time is spent for the travels between offshore wind farm and O&M port, maintenance tasks cannot be carried out. In addition, there is a safety restriction that the maintenance activities can only be performed when there is sufficient daylight at the offshore wind farm. Due to the fact that the length of days in winter is relatively short in the regions that the forthcoming offshore wind farm projects are planned such as UK, Germany, Norway, and Denmark, the restriction of starting maintenance activity after the sun rises decreases the operational window significantly in a regular maintenance day. These major difficulties influence the power production undesirably and increase the financial risks of the operating offshore wind farms.

By considering the wind farm case and the most favourable O&M fleet identified in Chapter 5, operational simulations are performed with respect to increasing distance between the wind farm and the conventional onshore base. The distance is increased from 10 nautical miles (nmi) to 100 nmi with 10 nmi intervals. By keeping all other parameters constant, it is possible to identify the real influence of increasing distance on the key outputs such as availability, O&M cost/MWh and revenue loss. In this respect, the key results of these simulations are shown in Figure 142-Figure 146. Figure 142 shows the change in the total O&M cost and wind farm availability with respect to the increase in distance. It can clearly be seen that there is an increasing trend in the total O&M

cost/MWh; on the contrary, there is a decreasing trend in the wind farm availability. It is envisaged that the theoretical power production can potentially increase due to stronger winds in far offshore, however the level of wind farm availability decreases considerably after a distance of 60 nm, which cannot be compensated by any aspect. Although travel distance increases and essentially fuel cost increases, the main reason of the cost increase is the decrease in power production.

Figure 143 shows the proportion of revenue loss to the theoretical revenue and the distribution of two major contributors (O&M cost and financial loss due to decrease in power production) with respect to increase in distance. The distribution is presented by vertical bar charts and the total revenue loss is presented by the black line. The revenue loss increases by the increase in distance; based on the initial simulations, 30% revenue loss for shorter distances increases up to 50% for longer distances. When the proportion of O&M cost and power loss to the total revenue loss is investigated, it can be seen that the share of O&M cost in the total revenue loss decreases, on the other hand, financial loss due to power production becomes dominant aspect in the distribution of total revenue loss. For instance, when the distance is 10 nmi, the revenue loss is approximately 27%, which the main reasons are O&M cost and financial loss due to power loss by 57% and 43%, respectively. When the distance is 100 nmi, the revenue loss is approximately 49%, which the main reasons are O&M cost and financial loss due to power loss by 24% and 76%, respectively. This is the indication that the power production cannot be sustained by the O&M performed.

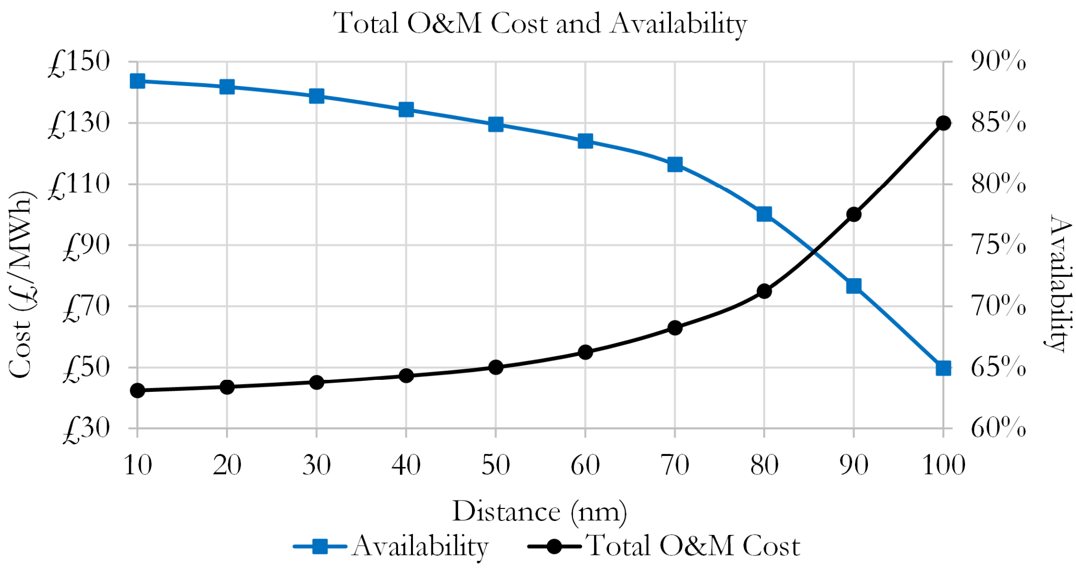

Figure 142: Total O&M cost and availability

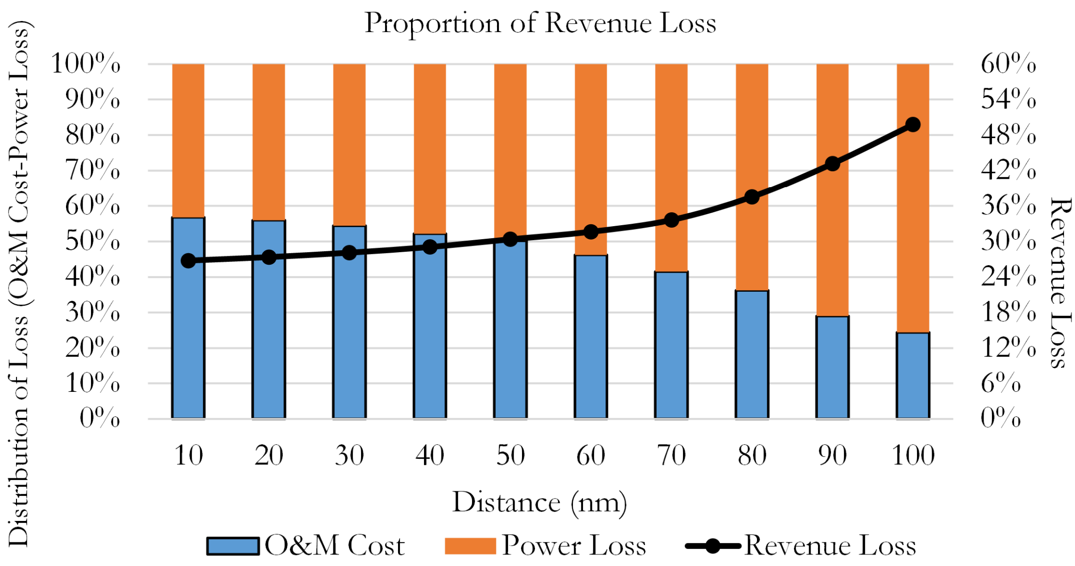

Figure 143: Proportion of revenue loss

In the previous sections, it was identified that fuel costs has a minor contribution to the total O&M cost. These trends can be explained in a better way, if the CTV travels, utilisation and accessibility aspects are investigated in depth. These aspects are demonstrated in Figure 144-Figure 146 with respect to increase in distance. As expected, average CTV travel increases, because a longer distance has to be travelled before allocation of the O&M technicians to turbines. Considering the fact that the length of working shift is constant (12 hours) in a repair day, average productive time and idle time decreases (Figure 144). When the distance becomes longer than 65 nm, O&M technicians start to spend more time on travels than the time spent on actual O&M activity. If the distance is 100 nm, CTVs travel more than 8 hours (outgoing and incoming) which leaves less than 4 hours for the O&M technicians to carry out O&M.

When CTVs are required to travel longer, the absolute CTV accessibility, in which the daylight and minimum working hour limitations are taken into account, decreases from 70% to almost 40% (Figure 145). Therefore, an accessibility of 140 days is expected, when the distance between offshore wind farm and O&M port becomes more than 70 nm. Average CTV utilisation is also related to the distance change. Due to the fact that the number of accessible days and the duration of weather window during these accessible days are significantly limited, the number of CTVs allocated to complete the repairs in a single repair day increases. This is also related to the number of failures in a single repair day. When the accessibility decreases, the number of failures increases by time; this is because these failures cannot be attended by the O&M technicians, especially in winter.

Figure 146 shows the internal and external travels of the CTVs with respect to increase in distance. Internal travel implies the travels between offshore wind turbines and external travel indicates the travels between offshore wind farm and O&M port. In this respect, the external travels (outgoing and incoming) increases significantly by the increase in distance. On the other hand, internal travels decrease; this is because longer external travels allow shorter internal travels. Since, the O&M technicians are allocated to the turbines in an order, and the external travel is required to be completed in order to allocate the first technician team; therefore, the increase in the external travels influences all other subsequent activities in that particular repair day.

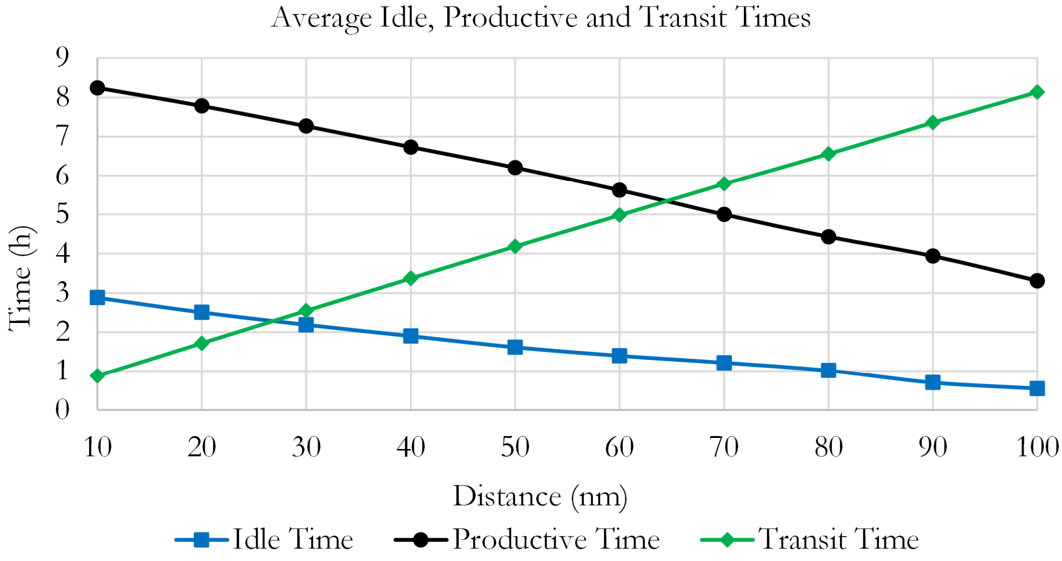

Figure 144: Average idle, productive and transit times

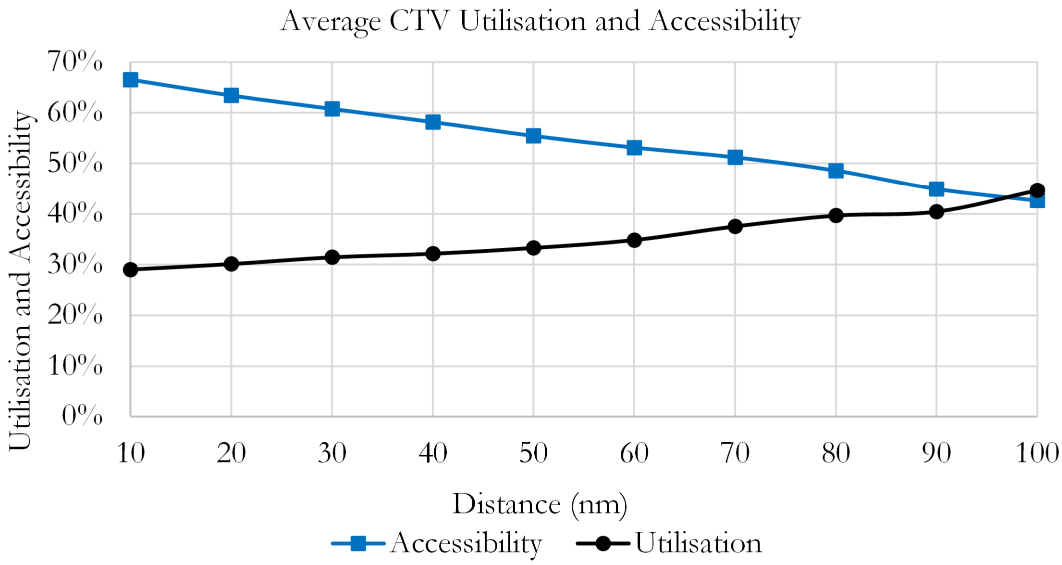

Figure 145: Average CTV utilisation and accessibility

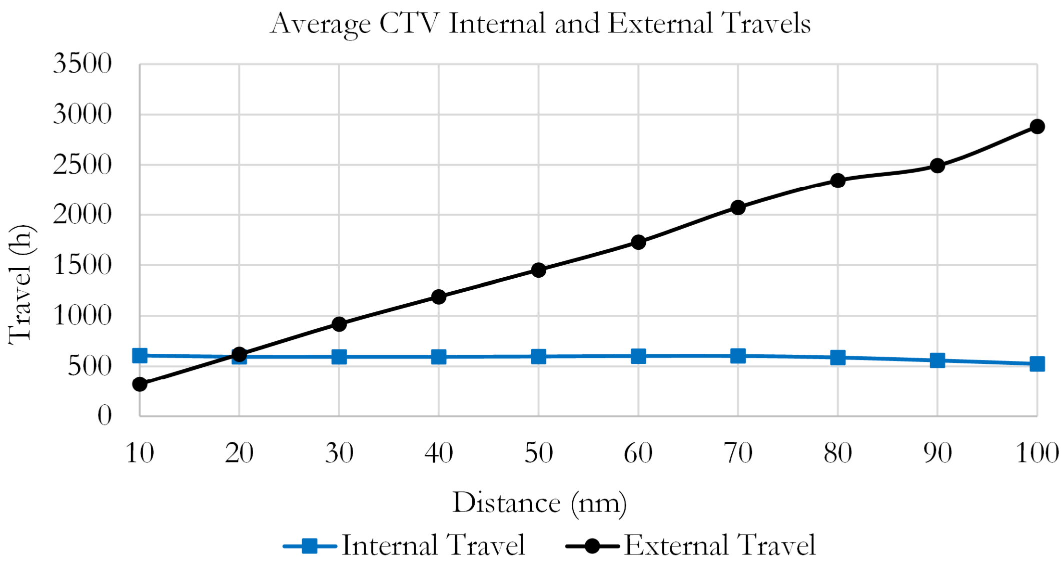

Figure 146: Average CTV internal and external travels

As a summary of what has been discussed so far in this section, an increase in total O&M cost/MWh and a decrease in availability are expected with respect to increase in distance between the offshore wind farm and O&M port. A mothership, which is a large vessel that can accommodate O&M technicians on-board and multiple crew transfer vessels alongside, can provide the solution for the operators. By considering a mothership in the O&M fleet, the reaction time to the failures can be minimised; thus the availability of the offshore wind farm can be maximised. Furthermore, the fuel costs can be decreased by eliminating the vessel travels between the O&M port and the offshore wind farm. The work hours can be more flexible as a result of personnel being on site and therefore, mothership concept can enable a much efficient use of limited weather window.

Despite these advantages, a strong enough financial case has not been made to consider a mothership in the O&M fleet. This is because a mothership requires a significant investment, and the benefits/drawbacks of considering a mothership in the maintenance fleet have not been investigated in a comprehensive way. Furthermore, knowledge related to the mothership operational practice is limited. In this respect, different chartering and operating strategies have to be investigated in order to optimise the offshore wind O&M activities.

6.3 Characteristics of the mothership

The mothership concept for the offshore wind industry is still under development. Although the potential benefits by considering a mothership in the O&M fleet have been investigated in recent times, there is no actual application within the industry. There are minor floating hotel applications (small ferry conversions) within the industry such as 'Wind Perfection' and 'Wind Solution' (C-bed Floating Hotels, 2014); however, these vessels are not purpose-built vessels; therefore, it is necessary to investigate dedicated mothership with extensive storage and workshop areas in order present the future offshore applications. In this respect, the mothership concept developed by Olsen et al. (2014) within the University of Strathclyde is identified to utilise in the case studies (Figure 147). In this context, Table 37 presents the mothership associated inputs. Moreover, Table 38 and Table 39 present the CTV and daughter craft inputs, which are categorised under mothership. The daughter craft characteristics in Table 39 are based on the report by Ribcraft Ltd (2014).

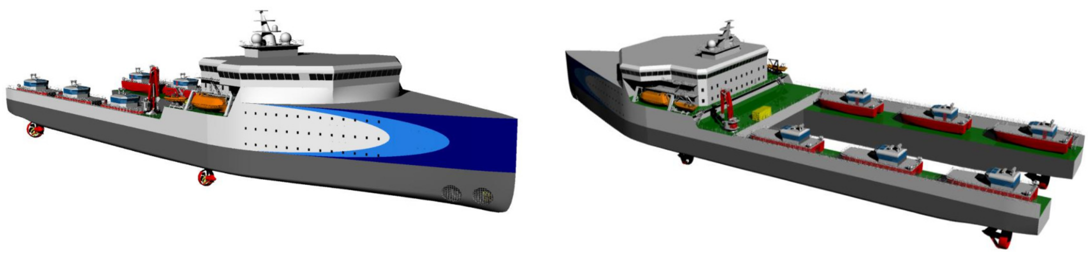

Figure 147: Mothership concept (Olsen *et al.*, 2014)

Table 37: Mothership inputs

Input Name	Type	Value	Unit
Operational speed	Operational	8.5	$knots$
Endurance	Operational	30	$days$
Time required to replenish	Operational	1	shift
Fuel consumption (stationary)	Cost	36.3	$tons/day$
Fuel consumption (operational)	Cost	72.6	$tons/day$
Number of crew	Cost	22	$-$
Wind speed at sea level	Survival	36.1	m/s
Wave height	Survival	7	m

Table 38: Mothership inputs (CTV associated)

Input Name	Type	Value	Unit
Number of CTVs moored	Operational	6	$-$
CTV Endurance	Operational	15	$days$

Table 39: Mothership inputs (Daughter craft associated)

Input Name	Type	Value	Unit
Number of daughter crafts	Operational	4	$-$
Technician Capacity	Operational-Cost	8	$-$
Fuel consumption	Cost	0.074	m^3/h
Wind speed at sea level	Operational	12	m/s
Wave height	Operational	1.0	m

For the mothership, following two concepts have been modelled and analysed;

- A floating hotel mothership concept: In this mothership type case, only CTVs can moor alongside, the mothership can be chartered for long-term or short-term/seasonal. The number of daughter crafts is set to '0' for the floating hotel mothership concept. It is assumed that the mothership is large enough to accommodate all the O&M technicians and CTVs including their crew at the same time.

- A pro-active mothership concept: In this mothership type case, CTVs can moor alongside, daughter crafts on-board also provide additional support. In the O&M activities, CTVs have the priority to be allocated. If there are still failures to be attended and if climate conditions allow, daughter crafts are allocated to the failed turbines. The mothership can be chartered for long-term or short-term/seasonal. It is assumed that the mothership is large enough to accommodate all the O&M technicians, CTVs and daughter crafts including their crew at the same time.

It is common that offshore personnel are on duty in 14 consecutive shifts of 12 hours each followed by 14 days of rest (HSE, 2008), in which they remain in the payroll; therefore, the personnel and associated costs are required to be multiplied by two. It is envisaged that both mothership concepts can operate 30 days in the offshore wind farm without any interruption. At the end of the shift of the 30^{th} day, the mothership travels back to port, replenishes fuel, fresh water, provision, etc. during the night. At the beginning of the next shift, the mothership travels to the offshore wind farm and this process is repeated within the charter period.

6.4 O&M fleet configurations and chartering alternatives

These two concepts are essentially unique vessel concepts, in which crew and O&M technicians can be accommodated, also these vessels incorporate well-equipped workshops. The major difference envisaged between these two concepts is the pro-active mothership has 4 daughter crafts on-board; so, if there are still unattended turbines after all the CTVs are allocated in a repair day, these daughter crafts can be utilised. Due to very high CAPEX, which offshore wind operators may avoid to invest in, it is envisaged that the mothership is chartered for certain period of time. Due to more advanced design, it is assumed that pro-active mothership concept has higher charter rate than the floating hotel concept.

In this context, major O&M fleet configurations, which are utilised in the simulations, are listed in Table 40. Three different O&M fleet configurations and nineteen different chartering alternatives are simulated for a period of 5 years. The distance between the offshore wind farm and the O&M port is set to 90 nautical miles. In order to identify the seasonal influence of climate and power production on the mothership utilisation, the charter periods are selected in order to cover summer months, winter months and combination of them. It is envisaged that, the mothership is always available during the simulation period for the 'Continuous charter' type. On the other hand, the mothership is only available for the specified periods within the 'Seasonal charter' type. In this context, the mothership is chartered each year within 'Start Month' and 'Final Month', inclusive. O&M activities performed through a conventional O&M port, when the mothership is not available at the site. Six CTVs and a single jack-up vessel, which their characteristics are presented in chapter 5, are considered within all the configurations.

By keeping all other parameters constant, it is possible to identify the real benefit by performing O&M activities by a mothership. A comparison can also be made by assessing the availability of the configuration no. 1 in Figure 148 and the simulation results of the other configurations. In this respect, it should be highlighted that availability of a particular month is not only dependent on the operations and climate within this month, it is also dependent on the availability of the previous months. If the availability is significantly low as in January, it takes time to repair failures that are piled up due to low accessibility and increase the availability to reasonable level as in summer months (Figure 148). On the contrary, when the availability is high as in July, even if the accessibility becomes lower for a certain period of time, the availability remains relatively high. Therefore, it is important to analyse the overall structure instead of individual localised areas.

Table 40: Simulated O&M fleet configurations

No	Configuration	Charter Type	Start Month	Final Month	Period	Daughter craft
1	No mothership	N/A	N/A	N/A	N/A	N/A
2	Floating hotel	Continuous	N/A	N/A	5 years	N/A
3	Floating hotel	Seasonal	Jan	Jun	6 months	N/A
4	Floating hotel	Seasonal	Apr	Sep	6 months	N/A
5	Floating hotel	Seasonal	Jul	Dec	6 months	N/A
6	Floating hotel	Seasonal	Oct	Mar	6 months	N/A
7	Floating hotel	Seasonal	Jan	Mar	3 months	N/A
8	Floating hotel	Seasonal	Apr	Jun	3 months	N/A
9	Floating hotel	Seasonal	Jul	Sep	3 months	N/A
10	Floating hotel	Seasonal	Oct	Dec	3 months	N/A
11	Pro-active	Continuous	N/A	N/A	5 years	4
12	Pro-active	Seasonal	Jan	Jun	6 months	4
13	Pro-active	Seasonal	Apr	Sep	6 months	4
14	Pro-active	Seasonal	Jul	Dec	6 months	4
15	Pro-active	Seasonal	Oct	Mar	6 months	4
16	Pro-active	Seasonal	Jan	Mar	3 months	4
17	Pro-active	Seasonal	Apr	Jun	3 months	4
18	Pro-active	Seasonal	Jul	Sep	3 months	4
19	Pro-active	Seasonal	Oct	Dec	3 months	4

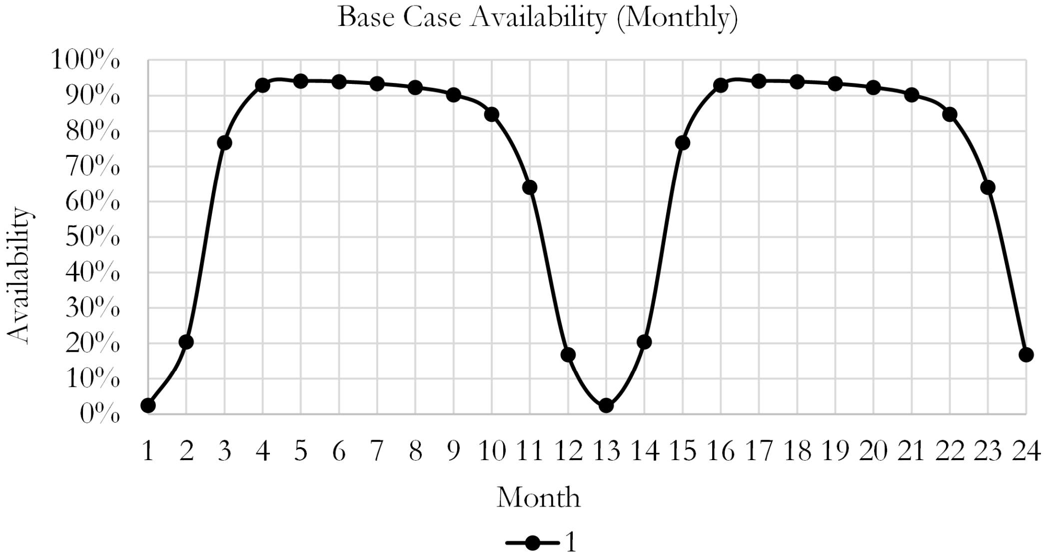

Figure 148: Availability with respect to months

6.5 Simulation results

6.5.1 Availability results

Figure 149 shows the change in the availability with respect to the configuration no. 1, so it is possible to demonstrate the availability change by considering a mothership in the O&M fleet. The horizontal axis of this figure refers to the configurations in Table 40. Since, configuration no. 1 is defined as the base case, the availability increase value is '0'. In generic, an increase in availability can be noticed; however, the benefit varies significantly. In this context, the configuration no. 2-6-11-15 (cluster no. 1) show the highest potential by over 30% to increase the availability; the configuration no. 3-5-7-10-12-14-16-19 (cluster no. 2) provides an availability increase within a range of 13%-23% and the configuration no. 4-8-9-13-17-18 (cluster no. 3) increase the availability less than 5%.

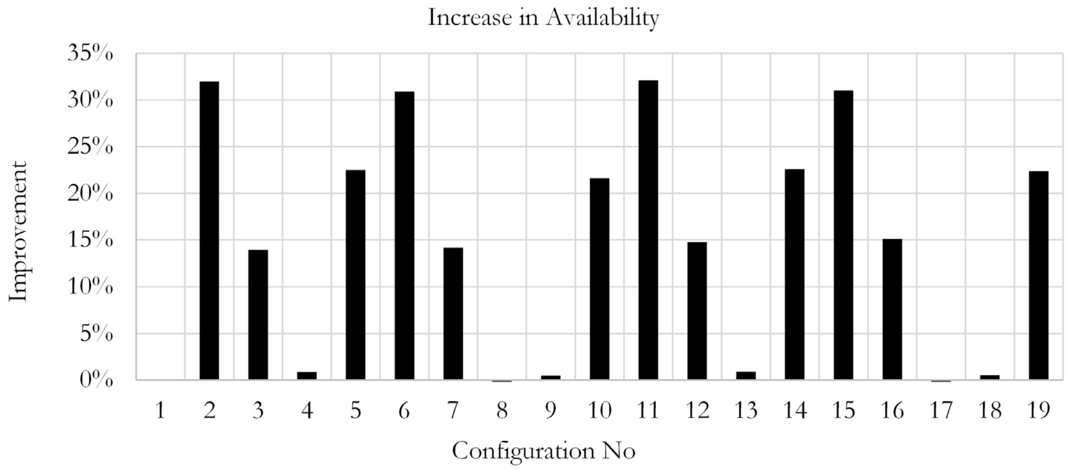

Figure 149: Increase in availability

For the configurations no. 2 and no. 11 in the cluster no. 1, the mothership is chartered for the entire simulation period (5 years); therefore, the O&M activities are mostly performed through the mothership. This results a major availability increase and eventually power production increase. The mothership is chartered between October-March in the configurations no 6 and no. 15; and therefore, the availability increase is lower than the configurations no. 2 and no. 11. When the common aspects are investigated among the configurations in the cluster no. 2, it can be seen that the charter periods cover either January-March or October-December. On the contrary, the configurations in the cluster no. 3 (the least preferable) do not cover the January-March or October-December periods; instead the mothership is chartered within summer months. Therefore, winter months (October-March) are identified as the most critical periods from availability increase point of view.

Considering the fact that the values in Figure 149 are the annual average values, the increase in the availability needs to be elaborated in depth in order to show the seasonality effect. In this respect, Figure 150 and Figure 151 demonstrate the change in the monthly availability values. The values in the figure legends refer to the configurations in Table 40. In order to show the change in each configuration and present the values in a more clear way, the configurations are divided into four different groups in an ascending order. The configuration no. 1 is defined as the base case scenario; therefore it is not demonstrated in this figure. Figure 150 and Figure 151 show that chartering the mothership between April-September does not bring a considerable advantage from availability point of view. Due to the fact that the climate is calmer relative to October-March period, and the duration of daylight period is even or more than 12 hours, the efficiency of the O&M activities are not improved as the other months. Regardless of the selected scenario (including the 'no mothership' configuration in Figure 148), the availability remains above 90% during summer.

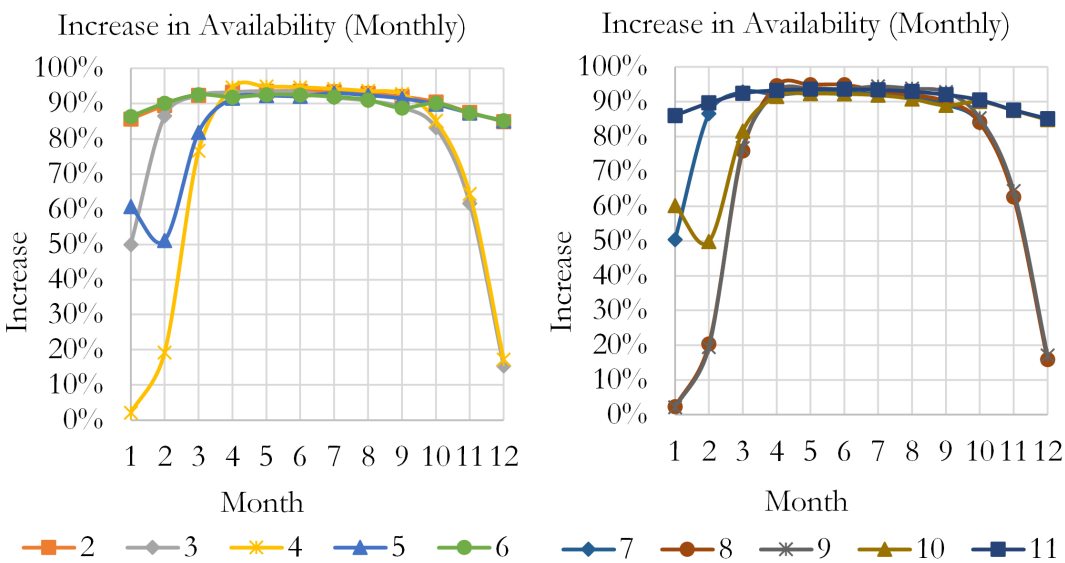

Figure 150: Increase in monthly availability

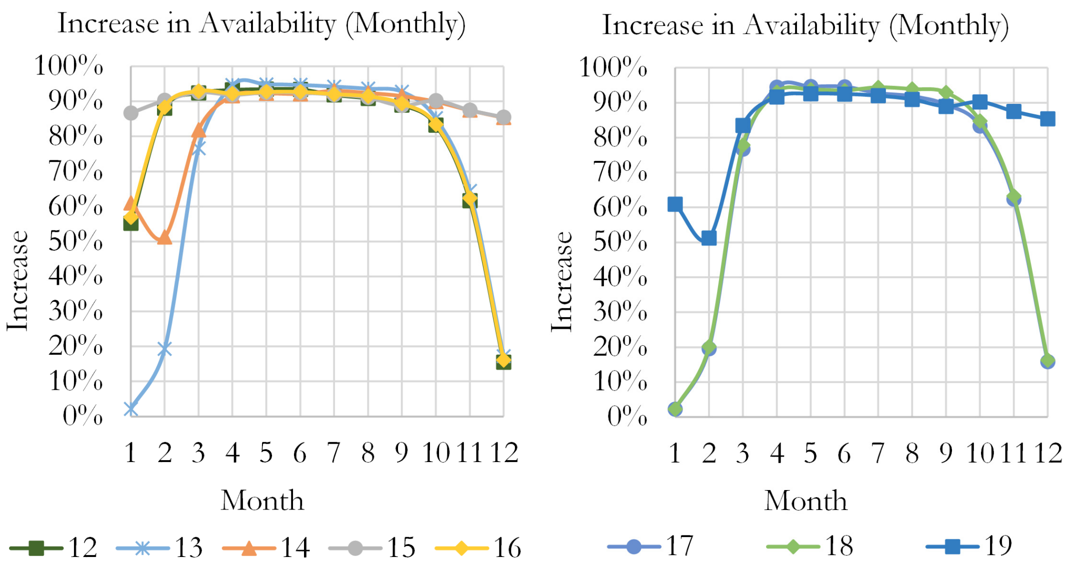

Figure 151: Increase in monthly availability

However, the winter availability varies significantly depending on the configuration selected. If the mothership is available in the offshore site in the second half of the year until December as in the configurations no. 5 and no. 14, the availability remains above 90% until December and immediately drops by January and continues decreasing in February due to accessibility limitations; it starts to increase again by March. If the mothership is available in the offshore site in the first half of the year until June as in the configuration no. 3 and no. 12, the availability increases, but remains relatively low (65%) in January. Although, the length of charters is same (6 months) and all four configurations cover 3 summer months and 3 winter months, the distribution of the availability is different. This is because, when the mothership is chartered in January and onwards, the availability drops in October-December period significantly; therefore, it takes all January to repair existing failures. On the other hand, when the mothership is in the site until December, the availability remains above 90%; therefore, even though the mothership is not available in January-March period, the overall (annual average) availability remains sufficiently high. This is a critical aspect that needs to be taken into account when a mothership is chartered.

6.5.2 Daughter craft associated results

When the comparison is made within the two mothership concepts ('Floating hotel' and 'Pro-active') from annual and monthly availability points of view, a small increase (less than 1%) is noticed. The reason of such a small difference is the fact that six CTVs bring a decent flexibility to the O&M activities; therefore, daughter crafts are rarely utilised in a repair day (Table 41). The travel hours shown in Table 41 are the average values; the maximum and minimum values are shown in the brackets. Due to allocation order, other daughter crafts are travelled in this value range. Considering the travels by the CTVs, the daughter craft travels are insignificant to improve the efficiency of the operations. Furthermore, additional crew and O&M technicians need to be employed for the operation performed by the daughter crafts, which may not be compensated.

The key outcome of the values in Table 41 is the accessibility and the associated charter seasons. The power production is improved by chartering the mothership in winter months as explained in Figure 151; however, the accessibility of the daughter crafts is significantly low in this period due to low operational limits. Therefore, the period, which the mothership is valuable for the operations is different than the period, which the daughter crafts can actually be utilised. In order to identify the importance of daughter crafts, additional simulations are performed by increasing the operational wave limit of the daughter crafts to 1.4 m and 1.8 m. All the other input values are remained constant. The change in the availability and average travels are presented in Table 42. Both availability and average travel hours are increased by the improvement in the operational wave height limit. However, the increase in availability is negligible compared to the increase achieved by considering the mothership in the fleet. Therefore, it is important to define the period that the mothership operates and increases the efficiency of the CTV operations instead of targeting the utilisation of daughter crafts.

Table 41: Daughter craft results

No	Start Month	Final Month	Travel hours (h)	Utilisation (%)	Accessibility (%)
11	Continuous		10.66 (16.56-6.41)	0.01	0.34
12	Jan	Jun	32.29 (34.98-29.95)	0.04	0.39
13	Apr	Sep	1.53 (2.59-0.89)	0.00	0.47
14	Jul	Dec	5.40 (8.51-3.05)	0.01	0.29
15	Oct	Mar	10.81 (15.91-6.89)	0.04	0.20
16	Jan	Mar	31.68 (34.29-29.35)	0.12	0.25
17	Apr	Jun	1.12 (1.52-0.79)	0.00	0.55
18	Jul	Sep	0.49 (0.96-0.22)	0.00	0.41
19	Oct	Dec	5.87 (8.71-3.58)	0.05	0.17

Table 42: Daughter craft operational wave height limit change

No	Operational Wave Height Limit					
	1.0 m		1.4 m		1.8 m	
	Availability	Travel hours (h)	Availability	Travel hours (h)	Availability	Travel hours (h)
11	0.908	10.6	0.910	36.0	0.921	191.1
12	0.789	32.2	0.796	63.6	0.807	142.1
13	0.693	1.5	0.693	6.3	0.697	58.0
14	0.843	5.4	0.850	18.5	0.851	106.5
15	0.901	10.8	0.903	32.0	0.907	134.7
16	0.791	31.6	0.799	60.2	0.803	117.6
17	0.684	1.1	0.689	2.9	0.689	23.8
18	0.691	0.4	0.691	2.9	0.691	34.9
19	0.841	5.8	0.842	17.7	0.851	73.9

6.5.3 CTV associated results

Figure 152 and Figure 153 show the change in CTV travels, utilisation and accessibility with respect to the change in configuration. Similar case as in Figure 149, the configuration no. 1 is defined as the base case; therefore, the changes for this configuration are set to '0'. Since, the motherships minimises the travels between offshore wind farm and port, the CTV travels decrease significantly, especially for the configurations, in which the mothership availability is maximised as in configuration no. 2 and no .11. In Figure 146, it was shown that external CTV travels has a decent share (increasing by distance) in the total CTV travels; mothership can eliminate 75% of the total CTV travels, which also decreases reaction time to failures and total fuel cost. CTV utilisation is directly related to the number of turbines that the CTVs can visit in a repair day. For instance, if there are six failures that need to be repaired in a repair day and if two CTVs can complete these six O&M tasks, the remaining four CTVs stay at the O&M port without being utilised. However, if the travel distance is long or the weather window is significantly short, six CTVs may need to be utilised in order to complete all the six O&M tasks in a single shift; in this case, the average utilisation increases. Figure 152 shows that there is relation between the CTV travels and utilisation aspects and the length of the mothership charter. Basically, the longer mothership is charted, the greater decrease can be achieved in CTV travels and utilisation.

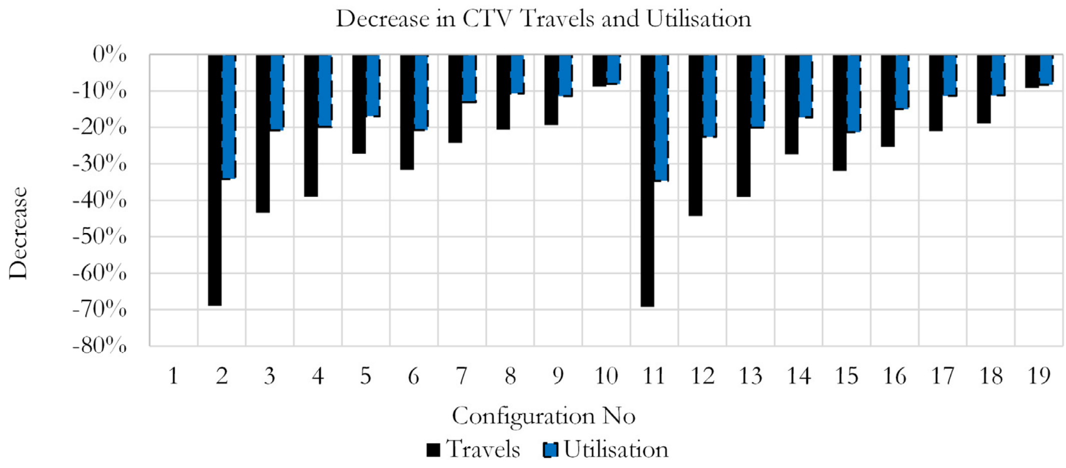

Figure 152: Decrease in CTV travels and utilisation

Figure 153 demonstrates the increase in CTV accessibility with respect to the change in the configuration. The configurations with longer mothership charter increases the accessibility of the CTVs considerably. When mothership is always available in the site, the accessibility can be increased more than 45% relative to the configuration without mothership. The major reason of this increase is the minimisation of external travels; therefore, when there is available working window, CTVs can be allocated immediately. On the other hand, if the travel distance is long and if the weather window is short, the CTVs cannot access the site.

When the increase in accessibility is assessed among the configurations with same charter length (6 months or 3 months), it can be seen that the winter charter increases the availability more than the summer charters. This is because, the accessibility is already high in summer; therefore, the accessibility increases by chartering the mothership in winter is considerably higher than the increase in summer. Due to the fact there is no actual difference in the CTV operations between two mothership concepts, the accessibility increase values are exactly the same.

Figure 154 shows the average MTTR values for turbine components and their variation by the change in the configuration. In this context, the configurations, in which the mothership is not chartered or charted only within summer months, result in the highest MTTR values. On the contrary, continuous or winter mothership charter result in a significant decrease in the MTTR values. Potentially (neglecting the supply chain issues), the MTTR values can be decreased from 450 hours to almost 50 hours by considering a mothership in the O&M fleet.

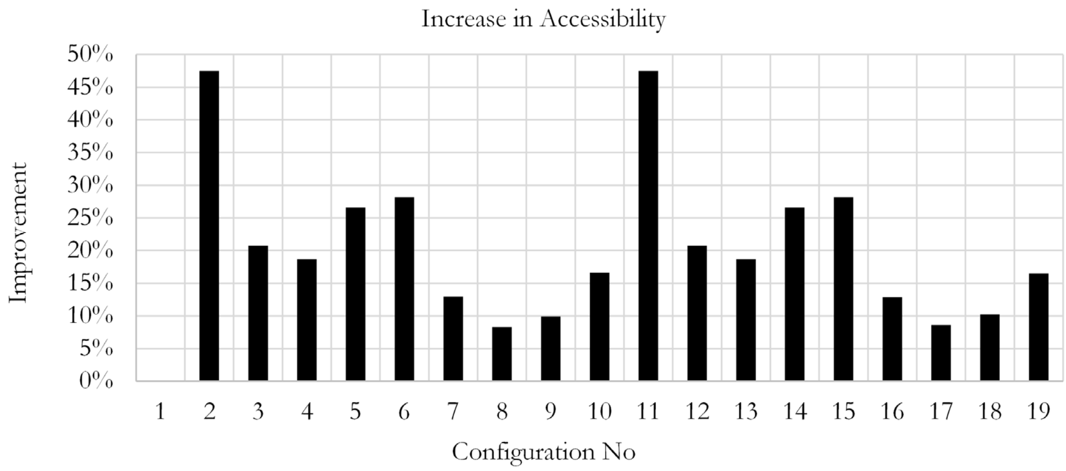

Figure 153: Increase in CTV accessibility

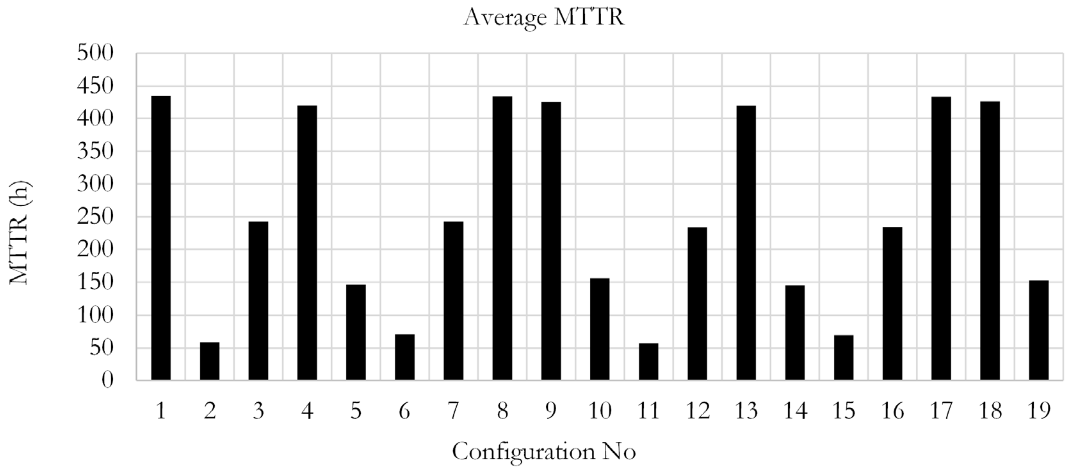

Figure 154: Average MTTR

6.5.4 Cost benefit analysis

Until this stage, the benefits of considering a mothership is assessed only from availability point of view. In order to make an accurate decision, the cost aspects also need to be investigated. Since, the mothership minimises the travels, it is expected that the longer mothership is chartered, the higher availability can be achieved. However, chartering a mothership for a longer period requires a considerable investment and associated costs are more likely to increase. Therefore, in this section, the costs and associated aspects about mothership charter are investigated in depth.

It is well known that the vessel charter rates are defined by vessel market, considering the balance between supply and demand. Due to the fact that there is no real application of a mothership, the mothership market has not been established yet. Although, there is potential mothership demand, the majority of the mothership studies are still at design stage; therefore, there is no particular charter rate defined for the motherships. In this context, the configurations in Table 40 are assessed by analysing different charter rates varying between £10,000 and £200,000 per day. It is envisaged that this charter rate range (£10,000-£200,000) is observed for similar size vessels in oil and gas industry. Figure 155 shows the total O&M cost change by the change in the daily mothership charter rates. Since the mothership is not chartered in the configuration no. 1, the total O&M cost remains as £100/MWh for this configuration. In order to make the comparison more clear, the configuration no. 1 is demonstrated in all the graphs as a reference point, so the reader can easily notice the positive and negative effects of the mothership and the change of the total O&M cost by increasing charter rates.

Essentially, the configurations in the cluster no. 3 do not bring an economic benefit, even for low charter rates; instead, they result in higher total O&M cost than the configuration no. 1. This is because, in these configurations, the availability is improved by less than 5%; and this increase is not sufficient enough to compensate the cost increase by considering a mothership in the O&M fleet, even for shorter charter periods. In generic, the configurations in the clusters no. 1 and no. 2 clearly bring an economic benefit relative to the configuration no. 1, even for excessive daily charter rates such as £200,000. The main reason of this conclusion is the fact that total O&M cost of the base case scenario is excessively high. The length of the mothership charter period influences the gradient of the graphs and the unit change by the increase in the mothership charter rate. Due to the fact that the mothership is charted for a longer term in the configurations no. 2 and no. 11, the total O&M cost increases rapidly by the increase in the mothership charter rate. For instance, the configuration no. 11 remains more cost effective than the configuration no. 10 until the mothership chart rate becomes equal to £120,000 a day. If the mothership charter rate becomes more than £120,000, the configurations no. 11 and similarly no. 2 lose their cost effectiveness against the configurations, in which the mothership is chartered in winter for shorter periods. Therefore, the daily charter rate is significantly important, when the decision about charter period is required to be made.

Table 43 shows the best four configurations with respect to associated mothership daily charter rates. The configurations no. 6, no. 2, no. 15, and no. 11 are identified as the most cost effective mothership charter configurations. Due to the fact that the mothership is not utilised during summer as effective as during winter, the configuration no. 6, in which the mothership is chartered for the 'October-March' period, is identified as the most favourable configuration. Although the charter periods are identical for the configurations no. 6 and no. 15 and the configurations no. 2 and no. 11, the 'Pro-active' mothership concept is more expensive than the 'Floating hotel' mothership concept. This is because daughter crafts increase the staff cost; however, the power production cannot be increased to compensate the associated costs.

Table 43: The best four configurations

	Configuration No.			
	6	2	15	11
Charter Period	October-March	Continuous	October-March	Continuous
Concept	Floating hotel	Floating hotel	Pro-active	Pro-active
Daily Charter Rate (£/day)	Total O&M Cost (£/MWh)			
10,000	34.42	34.67	35.57	35.81
20,000	35.25	36.31	36.40	37.44
30,000	36.08	37.95	37.23	39.08
40,000	36.90	39.58	38.05	40.71
50,000	37.73	41.22	38.88	42.35
60,000	38.56	42.86	39.71	43.98
70,000	39.39	44.49	40.54	45.62
80,000	40.22	46.13	41.37	47.25
90,000	41.05	47.77	42.20	48.89
100,000	41.88	49.40	43.02	50.52
110,000	42.71	51.04	43.85	52.16
120,000	43.54	52.68	44.68	53.80
130,000	44.36	54.32	45.51	55.43
140,000	45.19	55.95	46.34	57.07
150,000	46.02	57.59	47.16	58.70
160,000	46.85	59.23	47.99	60.34
170,000	47.68	60.86	48.82	61.97
180,000	48.51	62.50	49.65	63.61
190,000	49.34	64.14	50.48	65.24
200,000	50.17	65.77	51.31	66.88

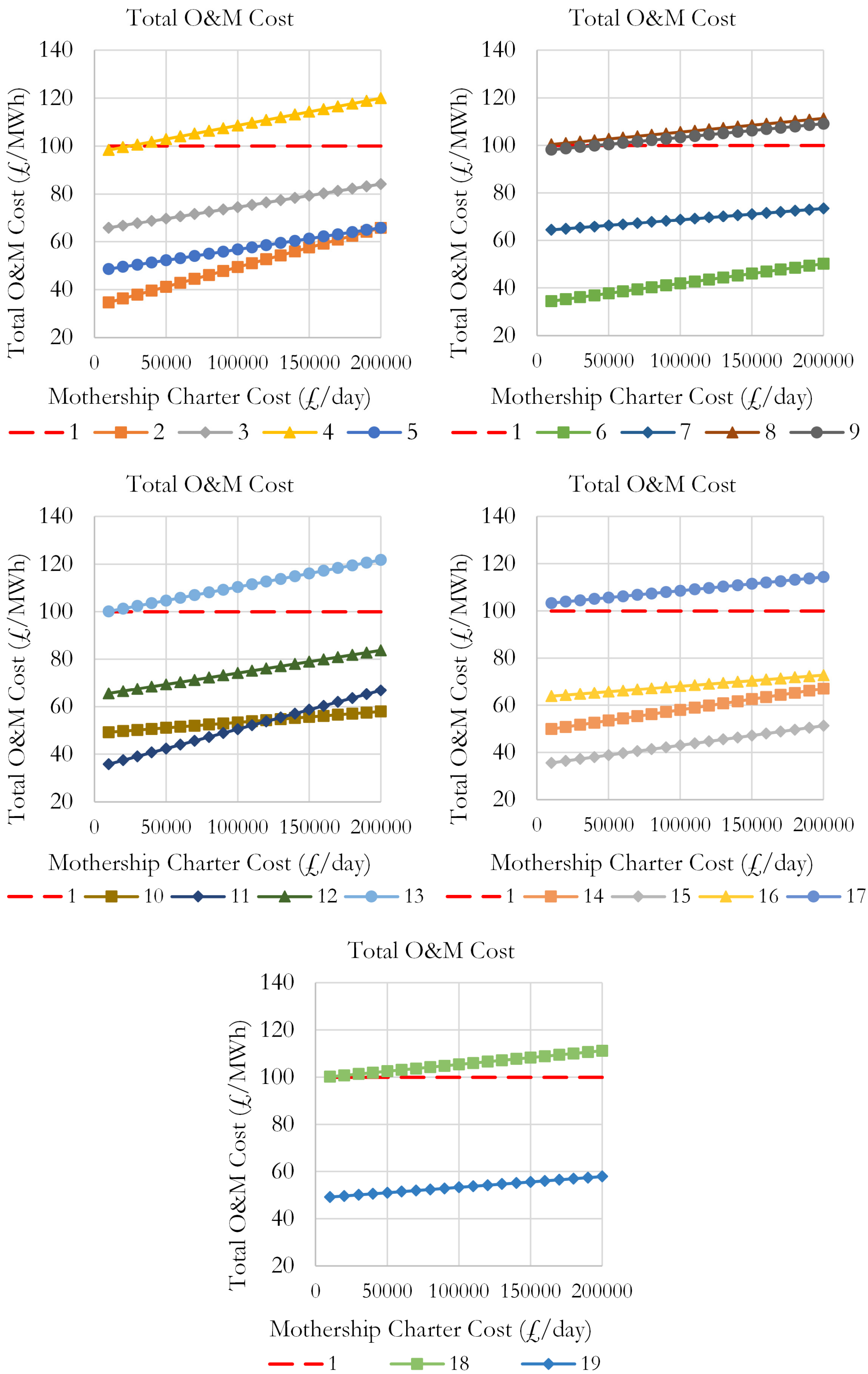

Figure 155: Change in the total O&M cost (3.6 MW turbine)

At this stage, it should be highlighted that all the configurations are compared and assessed relative to other configurations; however, a comparison also needs to be made, considering the current O&M costs and future prospects of the industry. Currently, the LCOE is approximately £140/MWh and it is expected that the LCOE will be £100/MWh by 2020 (PricewaterhouseCoopers, 2012, The Crown Estate, 2012). Considering the fact that the O&M cost accounts for 30-35% of the LCOE, a total O&M cost in a range of £30-35/MWh has to be targeted in order to remain cost effective and competitive. For instance, decreasing the total O&M cost from £100/MWh to £70/MWh is still not acceptable, considering the targets and future prospects.

If £35/MWh is defined as an upper limit for the decision, the majority of the configurations are still not applicable for any mothership charter rate, even though they decrease the total O&M costs. In this case, the configurations in the cluster no. 1 result in a total O&M cost less than £35/MWh but only if the mothership charter rate is less than £20,000. Motherships are envisaged to be large vessel (>150 m) (Wu, 2014); and considering the specification of the motherships, the charter rate of a mothership is more likely to be more than £20,000. At this stage, the turbine capacity and total power production has a crucial importance, since it can directly change the total O&M cost/MWh value. If the cost increase can be minimised, there is a great potential to improve the power production of the wind farm by installing high capacity turbines. This increases the turbine supply and installation costs; however, a significant reduction can be achieved and so, motherships can be a more valuable alternative for the offshore wind farm O&M. In this respect, in the following section, different turbine types are analysed to quantify their influence on the decision.

6.5.5 Change in the turbine capacity

In this section, the mothership charter is evaluated depending on the individual turbine production capacity. In this respect, 5.0 MW, 7.0 MW and 10.0 MW turbines are analysed by an identical approach as in the previous sections. It is expected that the cost of turbine components increases by the improvement in the turbine capacity. In this respect, it is assumed that the cost of components increases by the proportion of turbine capacity; therefore the cost of components are increased by 38% (5.0 MW/3.6 MW), 94% (7.0 MW/3.6 MW) and 177% (10.0 MW/3.6 MW) in these case studies. Due to the fact that the 'Pro-active' mothership concept does not bring a considerable advantage, the

‘Floating hotel’ is the only concept considered in this analysis; therefore, the number of configurations is limited by 10.

In this context, Figure 156-Figure 158 demonstrate the variation in the total O&M cost by the change in the mothership charter rate for 5.0 MW, 7.0 MW and 10.0 MW turbines, respectively. The generic shape of the graphs is similar to the 3.6 MW turbine graphs; however, the total O&M cost associated with each mothership charter category is shifted down. This is because, the power production is improved considerably but the costs are not increased as much as the level of power production increase. In all turbine types, the configurations no. 2 and no. 6 are identified as the most cost effective strategies for the mothership charter. These are the only configurations that the total O&M cost remains below £35/MWh. As in 3.6 MW turbine types, other configurations provide decent advantage in terms of cost reduction; however, even the reduced costs are much higher than the current O&M costs. Considering the fact that the offshore wind industry aims to decrease the costs, the configurations, which results in higher O&M costs than the current values are not acceptable for the future projects.

The gradient of the configuration no. 2 is higher in all the figures below, because the mothership is chartered for a longer period and always available on site; so, the unit charter rate increase influences the total O&M cost more than the configuration no. 6. For this reason, the configuration no. 2 is identified as the most valuable option, if the charter rates present a lower trend; on the other hand, if the charter rates are considerably high, operators can consider the alternative, in which the mothership is chartered only during winter months.

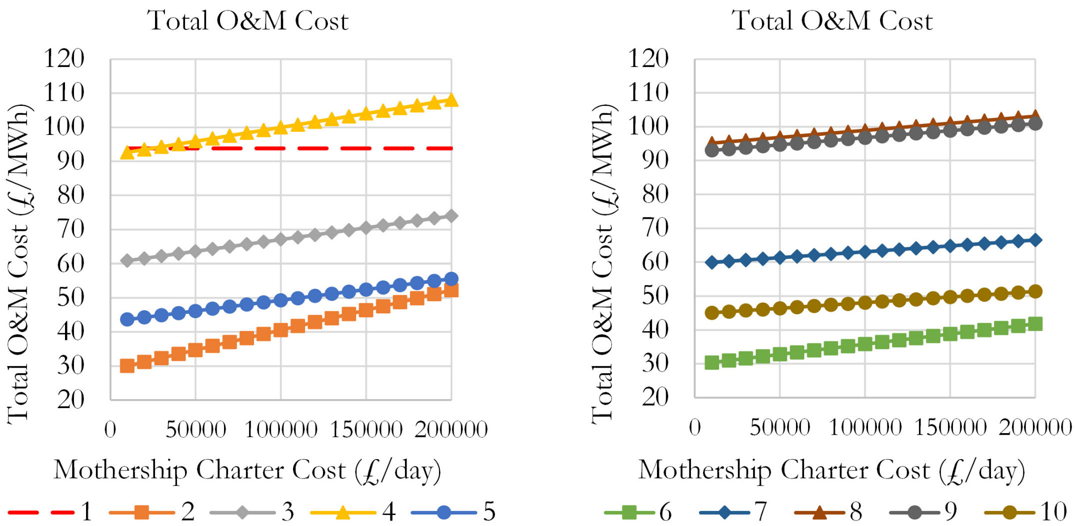

Figure 156: Change in the total O&M cost (5.0 MW turbine)

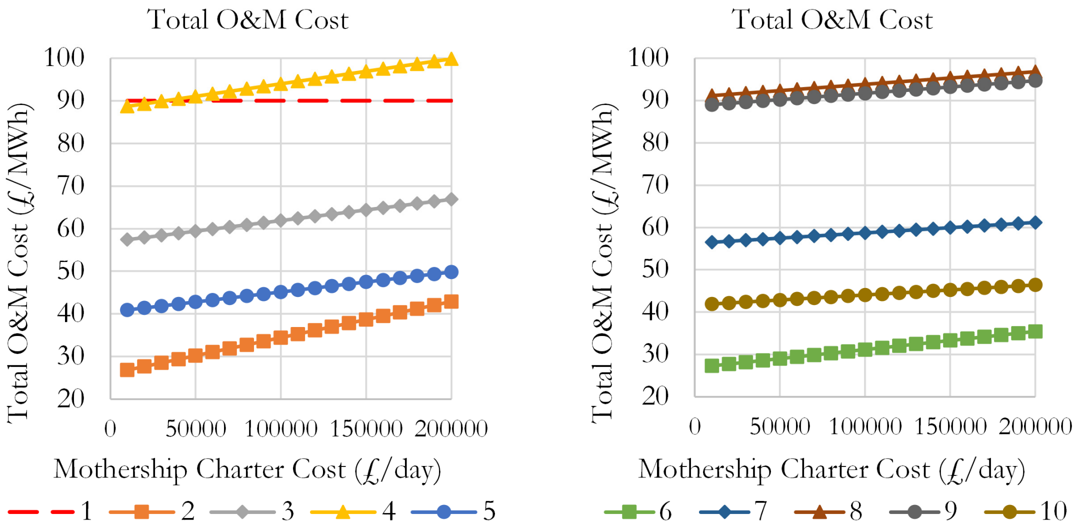

Figure 157: Change in the total O&M cost (7.0 MW turbine)

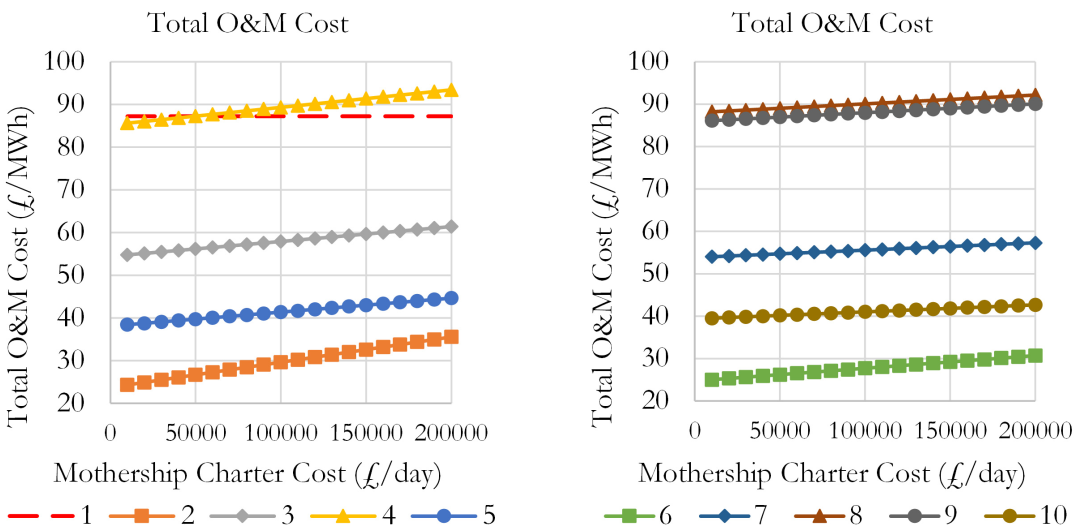

Figure 158: Change in the total O&M cost (10.0 MW turbine)

6.6 Final decision and conclusion

Considering what has been discussed so far in this chapter, the 'Floating hotel' concept is identified as a better alternative to 'Pro-active' mothership concept. Among the charter lengths and seasons, 'Continuous charter' type is identified as the most cost effective chartering option, if the daily charter rates show a lower trend. If the daily charter rates become higher, 'Seasonal charter' strategy becomes more cost effective and the 'October-March' period is identified as the most valuable chartering period (Figure 159). In this case, the operational and financial risks are also required to bear in mind, both having and not having the mothership in the O&M fleet. When the Round 3 projects start operating, the number of motherships can be insufficient to meet the demand by the operators. In this case, operators can still charter these vessels for longer periods in order to eliminate the vessel unavailability risk, even though the charter rates show a higher trend. The difference of winter and summer availability values can also lead the market to adopt seasonal charter rates instead of a fix day rate throughout the year, which is currently the case for the jack-up vessels.

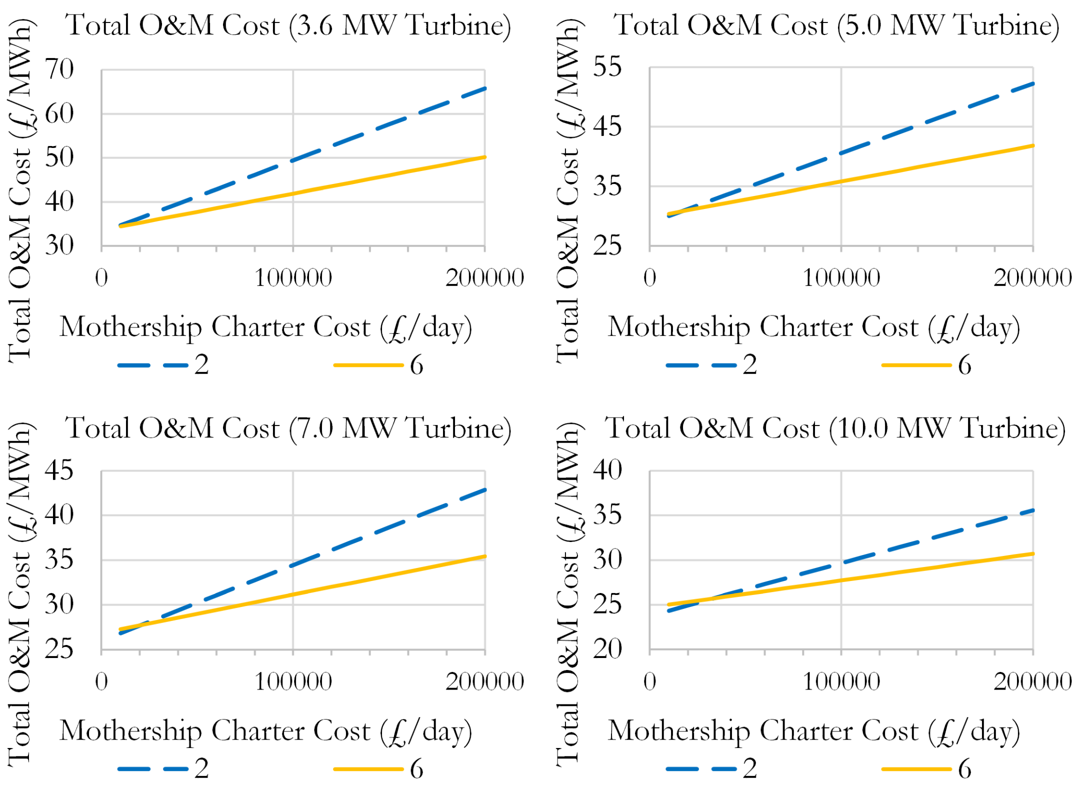

Figure 159: The change in the total O&M cost for the configurations no. 2 and no. 6

Furthermore, the generic criteria related to human performance are well established for seamen but not so well established for O&M technicians (Wu, 2014). Quality and duration of sleep are impaired by disturbance associated with ongoing tasks and environmental factors (e.g. noise, shared cabins, poor air quality) in offshore environment; and therefore can have adverse effects on day-to-day performance and alertness of the O&M technicians (Belenky et al., 2003, Anderson and Horne, 2006, Parkes, 2010, Townsend et al., 2012). Therefore, motherships are required to be analysed from human performance point of view in order to make a more accurate decision. It should be highlighted that the theoretical improvements cannot be achieved unless the practicality of these theories are well proven in every aspect.

6.7 Chapter summary

In this chapter, a particular focus is given to the mothership concept and its usage within the O&M fleet. Major charter periods, which include 'Seasonal charter (summer only)', 'Seasonal charter (winter only)', 'Seasonal charter (combination of winter and summer)' and 'Continuous charter', are investigated in order to achieve the lowest total O&M cost. Two different concepts, 'Floating hotel' mothership and 'Pro-active' mothership, are assessed in terms of availability increase and cost decrease. The results of the analysis show that the 'Continuous charter' and the 'Seasonal charter' between October-March bring significant operational and financial benefits. The 'Continuous charter' is more cost effective for low daily charter rates, while the 'Seasonal charter' between October-March is more cost effective if the charter rate increases.

6.8 References

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7 Sensitivity Analysis

7.1 Chapter outline

The robust methodology explained in the previous chapters provides flexibility to investigate the major aspects that affect the operational configuration and performance of the operating and forthcoming offshore wind farms. Although the major aspects that influence O&M are investigated, it is important to present that the simulation logic performs efficiently under different operating conditions, which are also important for the validation of the developed methodology. In this context, a detailed sensitivity analysis is performed in order to demonstrate the level of change in the financial and operational aspects, when there is a change in the simulation inputs. This provides the key information for the operators in the planning and the operational stage of offshore wind farms. After demonstrating the sensitivity analysis, this chapter is finalised by the chapter summary.

7.2 Description of validation process and definition of the base offshore wind farm case

7.2.1 Validation process

The validation process is a challenging task; because for complex systems, it is generally impossible or impractical to model the entire possible input domain and therefore, a simulation model can only be an approximation to the actual system regardless of time and money spent on the model development (Law, 2009). Even when a model is considered validated against an observable system, in which the wind farm with fully known climate, failure behaviour and operational procedures are known; when the model is used for alternative configurations, the fundamental assumptions may no longer be valid (Dinwoodie, 2014). There are various techniques available for model validation; the most commonly used validation methods and their descriptions, which are summarised in Table 44, are presented by Sargent (2010). In this context, the selection of the validation technique is significantly dependent on the characteristics of the developed model and the availability of external resources such as other tools, historical data etc. In this thesis, the 'parameter variability – sensitivity analysis' technique is selected for the model validation due to its practicality.

Table 44: Different validation techniques

Input Name	Description
Comparison to Other Models	Results of the simulation model are compared to results of other valid models.
Face Validity	Asking experts about the system whether the model and its behaviour are reasonable.
Historical Data Validation	If historical data exist, a part of the data can be utilised to build the model and the remaining data can be used for testing whether the model behaves as the system.
Parameter Variability – Sensitivity Analysis	This technique consists of changing the values of the input and internal parameters of a model to determine the effect on the model's behaviour of output.
Predictive Validation	The model is used to predict the system's behaviour, and then the system's behaviour and the model's forecast are compared to determine if they are the same.

7.2.2 Definition of the base offshore wind farm case

In this section, the base offshore wind farm case is explained. The further sensitivity analysis is performed by changing the inputs within this base case scenario. In this context, Table 45 shows the major inputs utilised in the base case scenario. In the simulations, the FINO data is used for the climate observations. In chapter 5, it was identified that the 26 m WFSV brings a significant benefit to the operations. It was also identified that the 21 m and the 19 m WFSVs are not the favourable options to be considered in the O&M fleet. Therefore, the 26 m WFSV is the only CTV type considered in the sensitivity analysis. The jack-up vessel characteristics, operational decisions, component failure rates and repair periods are assumed to be same as the case study in chapter 5. Due to the fact that these inputs are explained in chapter 5, the core information is provided in this section, but detailed explanation is not provided in order to prevent duplication. It is believed that 5 years is a reasonable period from O&M planning point of view; therefore the simulations are performed for a 5 year period.

Table 45: The inputs for the base case scenario

Input Name	Value	Unit
Number of turbines	100	$turbines$
CTV type	26 m WFSV	$-$
CTV Charter rate	3500	£
Jack-up vessel	MPI Resolution	$-$
Jack-up vessel CAPEX	73.11M	£
Wind turbine production capacity	3.6	MW
Distance to onshore O&M base	10	$nmiles$
CTV fleet size	[2,8]	$-$

7.3 Distance to O&M port

In this analysis, the distance to O&M port is investigated. In the majority of the existing studies, the distance is defined between the offshore wind farm and the closest onshore location. However, the closest onshore location may not be suitable for the installation of an O&M port due to various reasons such as inconvenient transport links, difficult vessel manoeuvres etc. The distance in this study is the average turbine distance to the O&M port. The analysis is performed for a range between 10 nmi (as the base case) and 100 nmi distance with 10 nmi intervals.

Figure 160 shows the change in the total O&M cost/MWh and availability with respect to increase in the distance from the O&M port. The total O&M cost increases while the availability decreases as the distance increases. An important aspect that needs to be highlighted is the decrease in the availability is not as high as the increase in the total O&M cost/MWh value. As they are explained in the previous sections, these aspects are the consequences of intermediate circumstances. Therefore, the root causes that increase the total O&M cost and decrease the availability need to be investigated in depth. In this respect, Figure 161-Figure 164 provide additional information about why the cost increases and the availability decreases.

Figure 161 illustrates the change in the O&M fleet configuration with respect to the increase in the distance. This figure clarifies the disproportional increase/decrease in the availability and the O&M cost/MWh value. When the number of CTVs is investigated in the O&M fleet, it can clearly be seen that the number of CTVs is increasing by the increase in the distance. When the distance is 10 nmi, 3 CTVs are enough to keep the availability around 90%, which results in £30/MWh total O&M cost. However, when the distance is 100 nmi, 8 CTVs are required to sustain the power production. Even in this case, the availability drops to 70%, which indicates that the power production is attempted to remain high by considering a larger O&M CTV fleet. However, the drop in the availability is inevitable; unless, an unconventional approach is implemented such as mothership, offshore fixed platform or surface effect ships (SES), for which 45 knots operational speed is applicable.

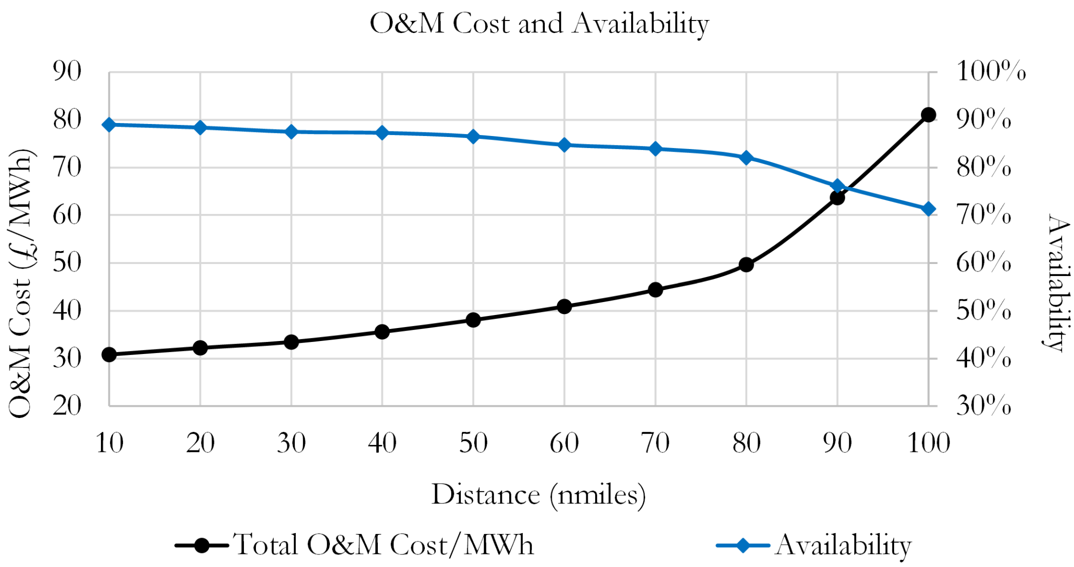

Figure 160: Total O&M Cost/MWh and availability

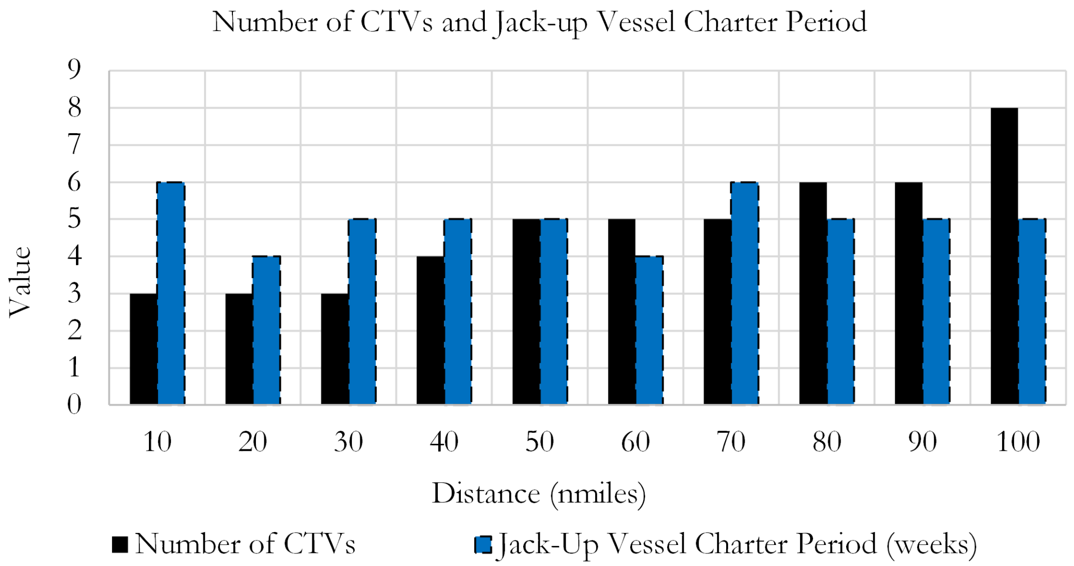

Figure 161: Number of CTVs and jack-up vessel charter period

In all configurations, the jack-up vessel is chartered for short-term (between 4-6 weeks). However, a significant relation is not observed between the jack-up vessel charter period and the distance to port. This is because the jack-up vessel does not need to be operated as frequent as the CTVs and if the climate conditions allow, the jack-up vessel can stay at the site until the endurance period is completed, which significantly decreases the number of travels.

Considering the fact that every cost aspect (fuel, staff, fixed costs) increases with a larger CTV fleet, a major root cause of the cost increase can be identified as the fleet size increase. Furthermore, and more importantly, the power production decreases, which does not increase the direct O&M cost (excluding financial loss due to low power production), but significantly increase the unit O&M cost. In this respect, the decrease in the power production is the second root cause for the total O&M cost/MWh value increase. To conclude what has been discussed about Figure 160 and Figure 161, the increase in the distance affects the costs in two ways: the first reason is the direct cost increase due to considering a larger CTV fleet, and the second reason is the indirect cost increase due to low power production.

It could be expected that considering a larger fleet for longer distances would sustain the power production as good as the power production for shorter distances. In order demonstrate why considering a larger CTV fleet may not be the solution to keep the power production high can be explained by interpreting the results in Figure 162-Figure 164. Figure 162 shows the distribution of the time spent in a working shift. The average travel time increases from 1 hour to 8 hours, if the distance is increased from 10 nmi to 100 nmi. On the other hand, the productive period decreases from 8 hours to 3 hours within the same distance values. In addition, the distribution of travels in Figure 163 shows that the increase in travels is due to the increase in the external travels not in the internal travels, which is not a favourable from operational point view. Spending time on external travels results in low operational efficiency. Furthermore, it decreases the absolute accessibility of the CTVs. This is especially important during winter. The required accessible weather window becomes longer by the increase in the distance, which results in decrease in the CTV accessibility.

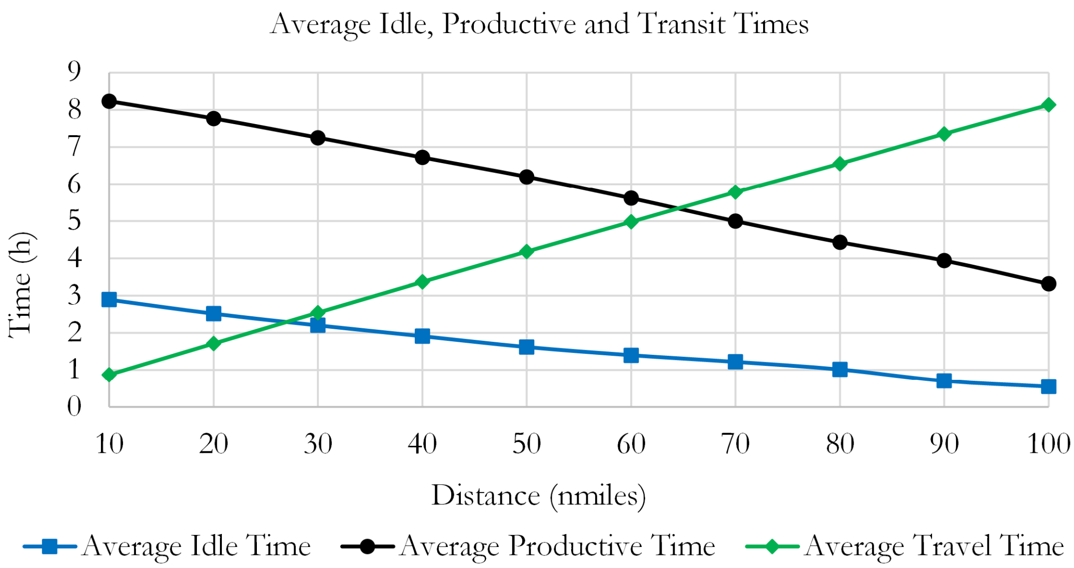

Figure 162: Average idle, productive and transit times

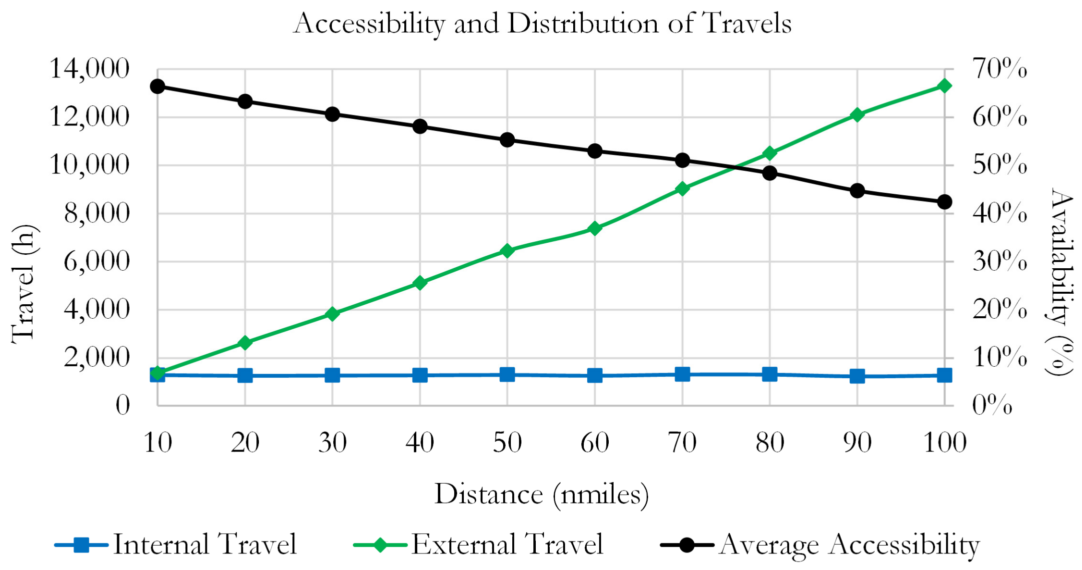

Figure 163: CTV accessibility and distribution of travels

The drop in the availability can be also noticed by interpreting the MTTR values in Figure 164. The average MTTR values for minor failures increase from 80 hours to 300 hours, when the distance is increased from 10 nmi to 100 nmi. Higher MTTR values imply that the turbines stay in failed condition longer, which decreases the power production and the availability. Similar to the jack-up vessel charter period, a significant relation is not observed in the MTTR values for major failures.

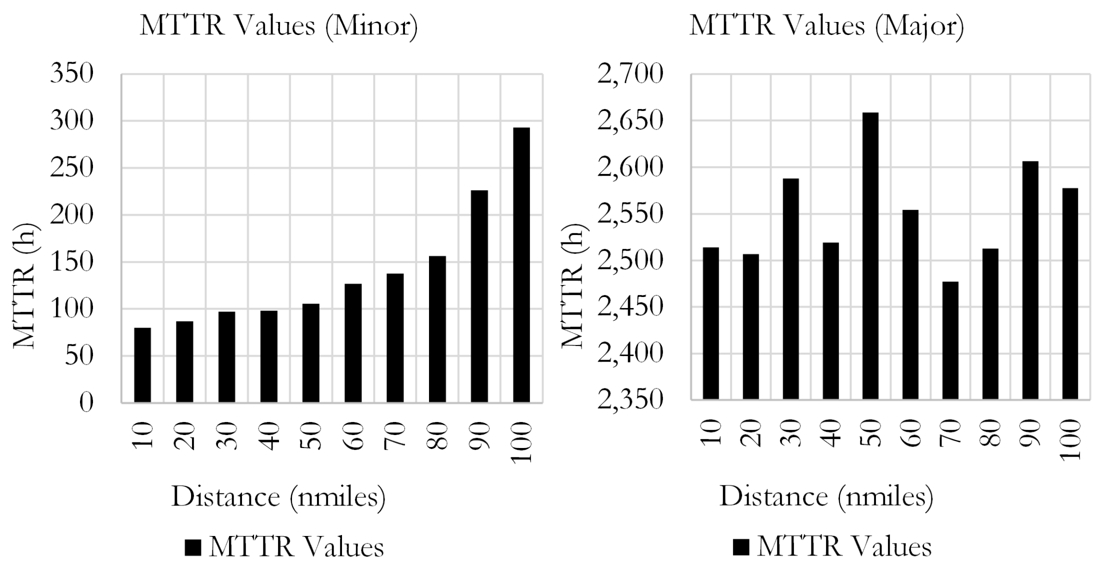

Figure 164: MTTR values

7.4 Component aging and failure rates

In this analysis, the age of the components is altered and the influence of this alteration on the O&M activities is investigated. In this respect, Table 46 shows the variety of the inputs considered in this analysis. Each row denotes a scenario and each column denotes an age interval. The values present the proportion of components that are fit into particular age intervals. For instance, in scenario no. 2, 95% of the components are brand new and the remaining 5% is at age 1. In a similar context, in scenario no. 3, 90% of the components are brand new, 5% is at age 1 and the remaining 5% is at age 2. In each scenario iteration, the number of new components is decreased by 5%, which is then added to another age interval.

By implementing this approach, the average age of the turbine components is increased, which changes the simulation interval of the failure rate distribution. Considering the fact that the failure rates are time dependent, it is believed that the age of the components has a significant importance on the performance of the offshore wind turbines. The age of the components is presented in a distribution, because it would be impractical to define and present the age of each component in the wind farm (100 turbines*12 components=1200 values). It is believed that this sensitivity analysis can be considerably important for the operators, especially when the warranty period is due to end. The operators can predict the costs in advance and therefore make more accurate decisions for forthcoming O&M contracts.

Figure 165 and Figure 166 show the change in the total O&M cost/MWh value and the availability with respect to change in the scenario. The values in the horizontal axis of these graphs refer to the scenarios in Table 46. It can be noticed that the distribution of the total O&M cost/MWh value is similar to the distribution of the failure rates. When the components are in wear-in stage the total O&M cost is below £30/MWh. When the average age of the components is shifted to the 'random failure' stage, the cost decreases. On the other hand, when the average age is increased towards wear-out stage and especially when the number of components with age 20 increases (after the configuration no. 21), the O&M cost starts to increase.

Table 46: The inputs for the sensitivity analysis

	Age distribution																				
Scenario no	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	95	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	90	5	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	85	5	5	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	80	5	5	5	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	75	5	5	5	5	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	70	5	5	5	5	5	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	65	5	5	5	5	5	5	5	0	0	0	0	0	0	0	0	0	0	0	0	0
9	60	5	5	5	5	5	5	5	5	0	0	0	0	0	0	0	0	0	0	0	0
10	55	5	5	5	5	5	5	5	5	5	0	0	0	0	0	0	0	0	0	0	0
11	50	5	5	5	5	5	5	5	5	5	5	0	0	0	0	0	0	0	0	0	0
12	45	5	5	5	5	5	5	5	5	5	5	5	0	0	0	0	0	0	0	0	0
13	40	5	5	5	5	5	5	5	5	5	5	5	5	0	0	0	0	0	0	0	0
14	35	5	5	5	5	5	5	5	5	5	5	5	5	5	0	0	0	0	0	0	0
15	30	5	5	5	5	5	5	5	5	5	5	5	5	5	5	0	0	0	0	0	0
16	25	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	0	0	0	0	0
17	20	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	0	0	0	0
18	15	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	0	0	0
19	10	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	0	0
20	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	0
21	0	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
22	0	0	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	10
23	0	0	0	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	15
24	0	0	0	0	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	20
25	0	0	0	0	0	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	25
26	0	0	0	0	0	0	5	5	5	5	5	5	5	5	5	5	5	5	5	5	30
27	0	0	0	0	0	0	0	5	5	5	5	5	5	5	5	5	5	5	5	5	35
28	0	0	0	0	0	0	0	0	5	5	5	5	5	5	5	5	5	5	5	5	40
29	0	0	0	0	0	0	0	0	0	5	5	5	5	5	5	5	5	5	5	5	45
30	0	0	0	0	0	0	0	0	0	0	5	5	5	5	5	5	5	5	5	5	50
31	0	0	0	0	0	0	0	0	0	0	0	5	5	5	5	5	5	5	5	5	55
32	0	0	0	0	0	0	0	0	0	0	0	0	5	5	5	5	5	5	5	5	60
33	0	0	0	0	0	0	0	0	0	0	0	0	0	5	5	5	5	5	5	5	65
34	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	5	5	5	5	5	70
35	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	5	5	5	5	75
36	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	5	5	5	80
37	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	5	5	85
38	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	5	90
39	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	95
40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	100

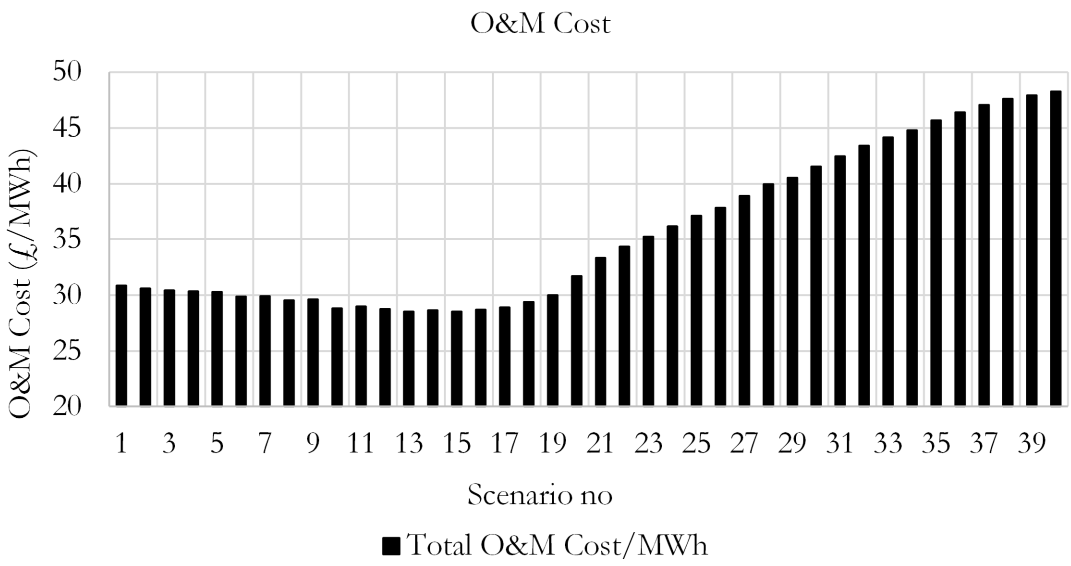

Figure 165: Total O&M cost/MWh

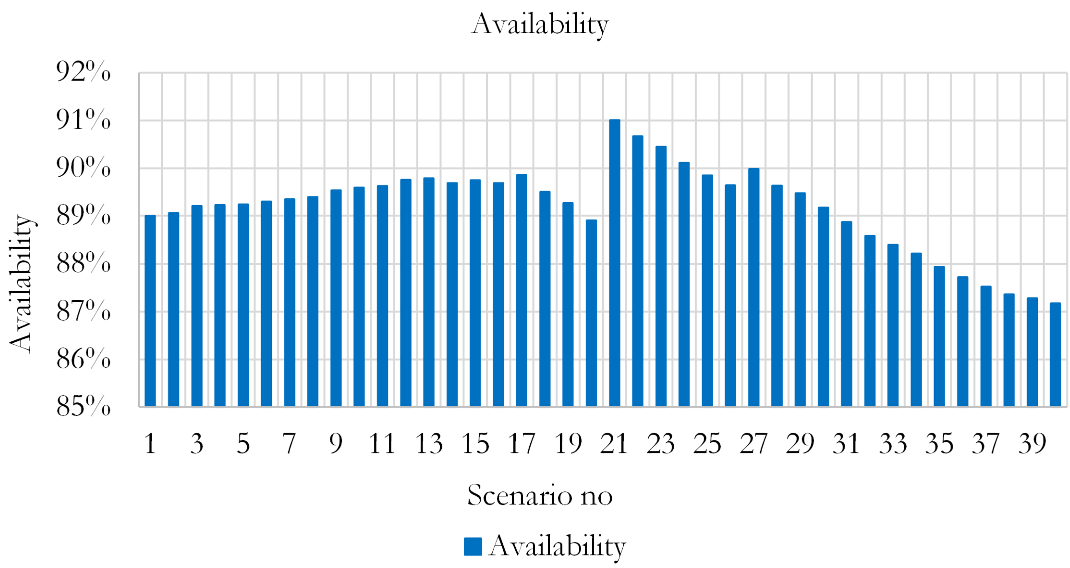

Figure 166: Availability

The distribution of the availability has a different shape compared to the O&M cost distribution. At the wear-in stage, the average availability slightly increases. The availability then starts to decrease by the increase in the average age of the turbine components. However, the availability makes a peak at the scenario no. 21 and then again decreases. The key change in the configuration no. 21 and onwards is the jack-up vessel charter type. The jack-up vessel is chartered for short-term within the configurations no. 1 and no. 20. On the other hand, the jack-up vessel is chartered for long-term (5 years) within the configurations no. 21 and no. 40. This is because the turbine component failure rates increase at the end of life cycle. It becomes unpractical and uneconomic to charter the jack-up vessel from spot market due to high charter rates and required repair period. In this respect, chartering the jack-up vessels for long term results in an increase in the availability, because it eliminates the mobilisation time and decreases the MTTR values. However, long term vessel chartering is not enough to keep to costs low.

In order to elaborate the increase in O&M cost, the total OEM cost and its distribution are also needed to be observed. In this respect, Figure 167 shows the cost distribution of turbine components within different scenarios. Similar to the total O&M cost distribution, the OEM cost has a decreasing trend in the early periods of the wind farm. Likewise, both the cost of minor and major components increase when the average age of the wind farm increases. Moreover, a disproportional increase is observed in the total cost of major components compared to the cost of minor components. This situation is related to the unit cost of the major components. Considering the fact that a major component repair costs £159,250 and a minor component repair costs £6,000 on average, the increase in the total OEM cost can be associated with the repair of major components.

Figure 168 shows the distribution of CTV travels with respect to scenario alteration. Likewise, the distribution of total CTV travels preserves a bathtub shape. The internal and external travels show similar trends, a decreasing trend during wear-in stage and an increasing trend during wear-out stage. An increase in the number of failures requires high number of visit; therefore, the CTV travels increase.

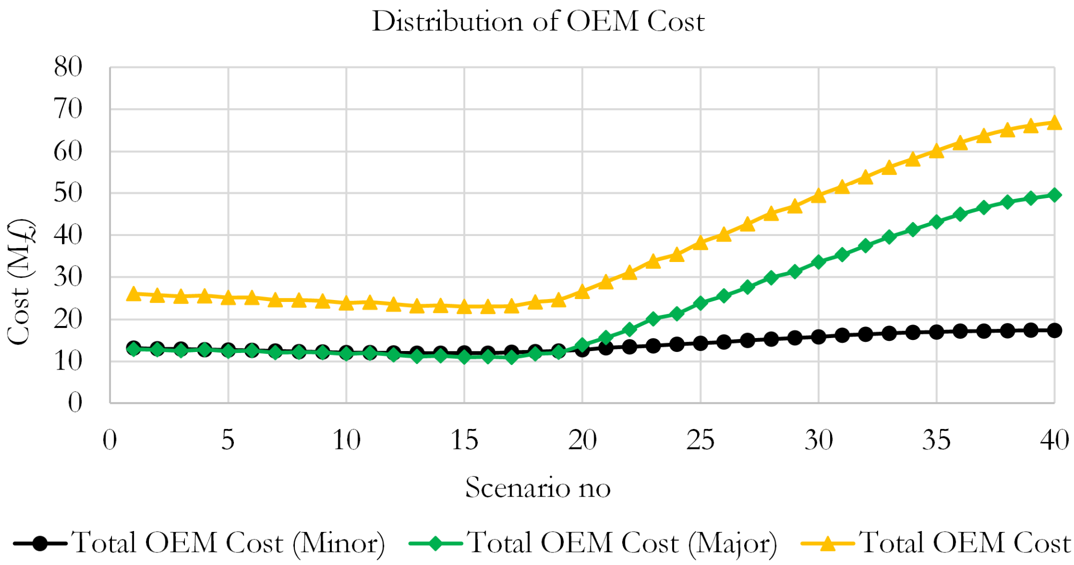

Figure 167: Distribution of total OEM cost

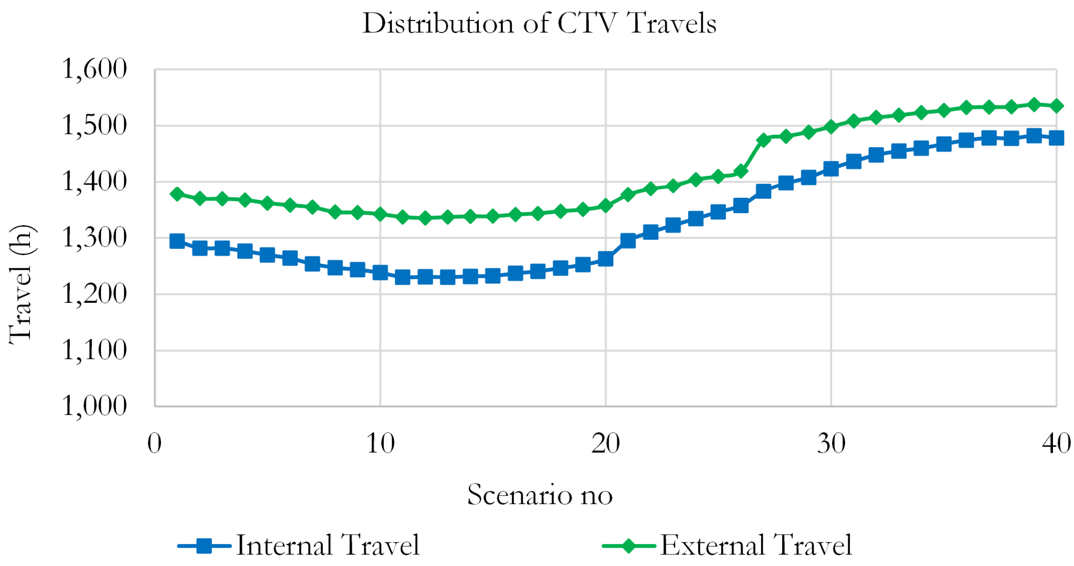

Figure 168: Distribution of CTV travels

At this stage, there is a crucial aspect that needs to be highlighted. When the bathtub distribution and the initial assumption that the condition of the repaired components is 'as good as new' are taken into account, operating a wind farm with a high average age is significantly unfavourable. This is because the failure rates are high in the wear-out stage and when these components are repaired, their location in the failure rate distribution is shifted to wear-in stage, in which the failure rates are also high compared to random failure stage of the lifecycle. Therefore, the failure rates remain high, even though O&M is planned in advance.

To conclude the aging and the failure rate sensitivity analysis, it is identified that the age and eventually the failure rate of the turbine components have a significant importance on the operational and financial O&M decisions. In the early years of operation, the operational costs decrease with the decrease in the failure rates. However, this situation is more likely to change at the end of turbine life time. In wear-out stage, the components fail more frequently; therefore, total O&M cost increases. This analysis also provides a key output regarding the validity of the O&M decisions. It is so unlikely to make decision, which can be accurate for the entire life of the offshore wind turbines. Due to the fact that failure rates are time dependent, the O&M planning needs to be reviewed and may need to be revised within specific intervals. Otherwise, the decisions made for short-term/mid-term may no longer be valid, if the failure rates increase/decrease.

7.5 CTV and jack-up vessel daily charter rates

In this analysis, the daily charter rates are altered in order to identify the change in the total O&M cost/MWh value. Due to the fact that the vessel charter rates are defined by the vessel market and also dependent on the supply-demand balance, it is important to examine the profitability of the operations under changing vessel cost. In this respect, the daily charter rate of the 26 m WFSV is increased from £3500/day to £8500/day with £1000/day intervals. In the developed methodology, the daily charter rate of the jack-up vessel is modelled in a relation with the vessel CAPEX. In this respect, the jack-up vessel CAPEX is increased from £73M to £150M. It is accepted that the vessel CAPEX does not change for a specific vessel; however, due to vessel unavailability, operators may need to charter a jack-up vessel, which is beyond the optimum requirements of the site and turbines. Chartering a jack-up vessel with higher operational capabilities and eventually higher CAPEX is likely to increase the daily charter rate of the jack-up vessel.

The alteration of the total O&M cost/MWh due to change in the CTV daily charter rate is demonstrated in Figure 169. When the CTV charter rate is £3500/day, the total O&M cost remains below £31/MWh and the total CTV charter cost within the simulation period (5 years) is £20M. As expected, when the daily charter of the CTVs is increased, both the total CTV charter cost and total O&M cost/MWh value increase. The increase in the total CTV charter cost is proportional to the increase in the daily charter rate. On the other hand, increasing the daily charter rate by 242% (from £3500/day to £8500/day) results in an increase in the total O&M cost by 12%.

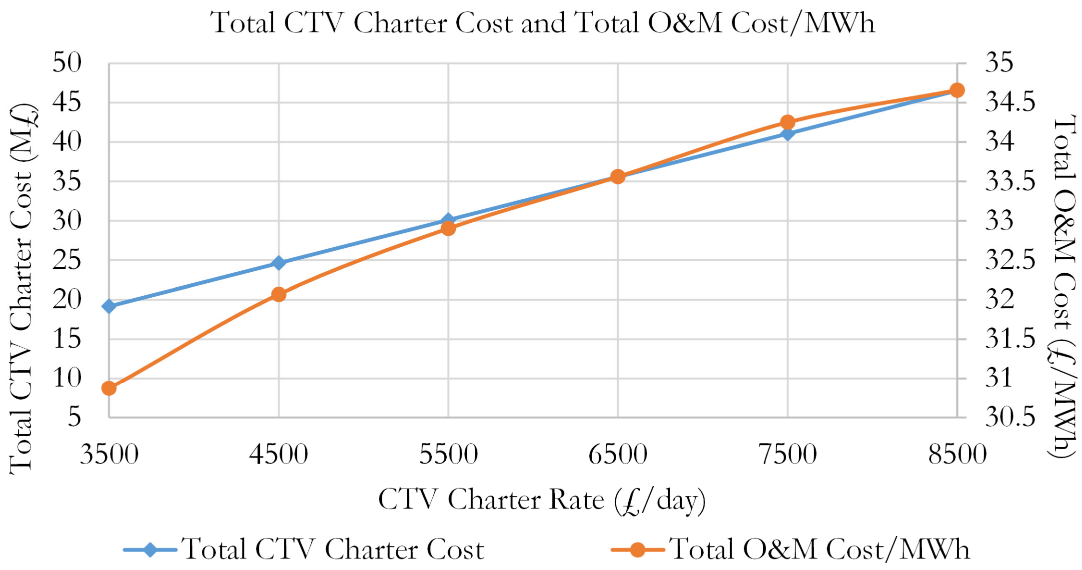

Figure 169: Total CTV charter cost and total O&M cost/MWh

Figure 170-Figure 172 show the distribution of daily charter rates observed in this sensitivity analysis. Due to the fact that jack-up vessel daily charter rates are selected from particular distributions, the values observed in the simulations bring uncertainty to the calculations. In these figures, it can be noticed that the distribution of the observed charter rates is shifted to right, which indicates the high charter rate area. The long-term charter rates are lower than the short-term charter rates. Similarly, the short-term charter rates in summer are higher than the short-term charter rates in winter. Although the operational risks are not quantified in this thesis, chartering the jack-up vessel for 5-years is more risky than short-term chartering.

Figure 173 shows the distribution of total jack-up vessel charter cost and the total O&M cost/MWh with respect to the change in the jack-up vessel CAPEX. As in the CTV daily charter rate increase, the total charter cost and the total O&M cost/MWh increase. In the first two scenarios (£73M and £90M CAPEX), the jack-up vessel chartered for a 6 weeks period. When the CAPEX is £110M and onwards, the jack-up vessel is chartered for a 5 weeks period. Therefore, the proportion of the regular charter payment to the penalty charter payment decreased. This is about balancing the total direct O&M cost and the power production. Basically, when the jack-up vessel charter rates increase, it is more favourable to charter the vessel for 5 weeks instead of 6 weeks. Despite the change in the charter period, the total jack-up vessel charter cost and the total O&M cost/MWh increase by 229% and 24%, respectively.

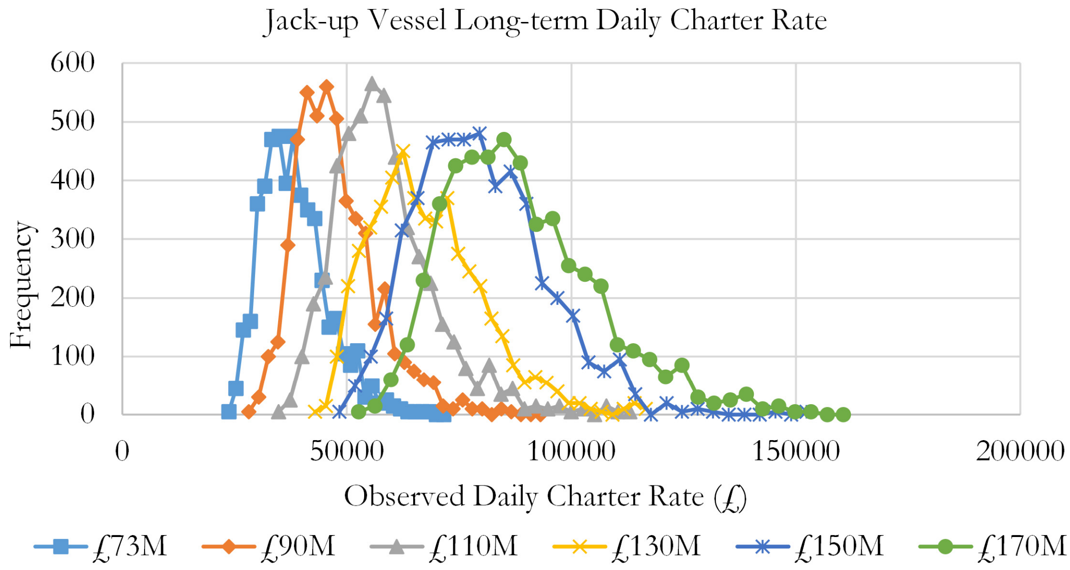

Figure 170: Distribution of observed jack-up vessel long-term daily charter rates

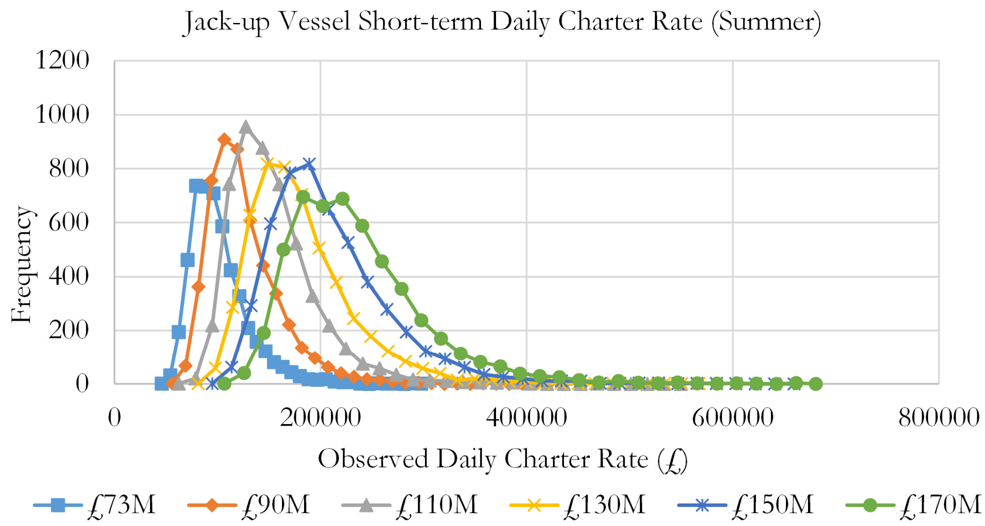

Figure 171: Distribution of observed jack-up vessel short-term daily charter rates (summer)

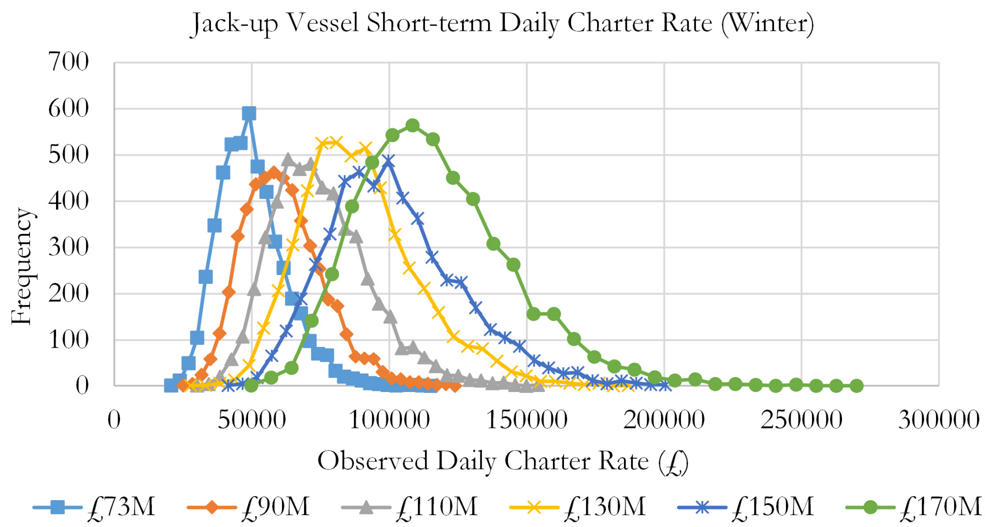

Figure 172: Distribution of observed jack-up vessel short-term daily charter rates (winter)

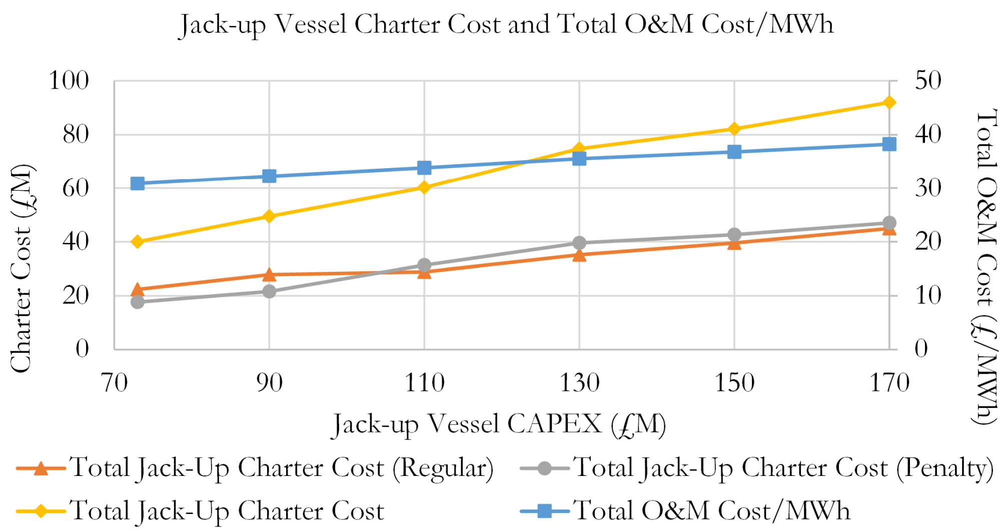

Figure 173: Jack-up vessel charter cost and total O&M cost/MWh

7.6 Wind farm size and capacity

In this analysis, the wind farm size (number of turbines) and the individual power production capacity of the turbines are altered. At the first stage, the simulations are performed for the wind farms, which consist of 100, 150, 200 and 250 turbines. At the second stage, the turbine power production capacity is increased to 5.0 MW, 6.15 MW and 10 MW, which is 3.6 MW in the base case scenario. The key results of these simulations are shown in Figure 174-Figure 177.

Figure 174 shows the change in the total O&M cost/MWh value and the availability for the identified offshore wind farm cases. Considering the fact that other aspects are remained constant, there is clear decline in the total O&M cost/MWh value due to the increase in the power production. However, although the number of turbines is increased, the availability is not decreased. It could be expected that the availability would decrease due the fact that the number of failures would be higher for the larger wind farms. The increase in the availability can be explained better, if the size of the CTV fleet and the charter period of the jack-up vessel in Figure 175 are elaborated. The increase in the number of turbines has a strong influence on the size of CTV fleet. The number of optimum number of CTVs is 3, 5, 7 and 8 for the 100-turbine, 150-turbine, 200-turbine and 250-turbine cases, respectively. Similarly, there is a change in the jack-up vessel charter period. In the base case scenario, the jack-up vessel is chartered from spot market for a 6 weeks period. When the number of turbines is increased to 150 and onwards, the long-term vessel charter alternative (this is denoted by 260 weeks in this figure, which is equal to 5 years) becomes more cost effective and more favourable from operational point of view.

These two factors allow to keep the wind farm availability for larger sites as high as the availability for smaller sites and decrease total O&M cost/MWh. However, an important aspect needs to be pointed out. Operating a 250-turbine wind farm can be significantly complicated than operating a 100-turbine wind farm. Supply chain issues can potentially arise. Moreover, there is a higher risk to operate a larger CTV fleet, in which extra measures may need to be taken such as extra staff training, improve infrastructure. These improvements result in an increase in the cost. Therefore, although the results are reasonable based on the assumptions, it is believed that the decrease in the total O&M cost/MWh value may not be as high as the simulation results in the real environment.

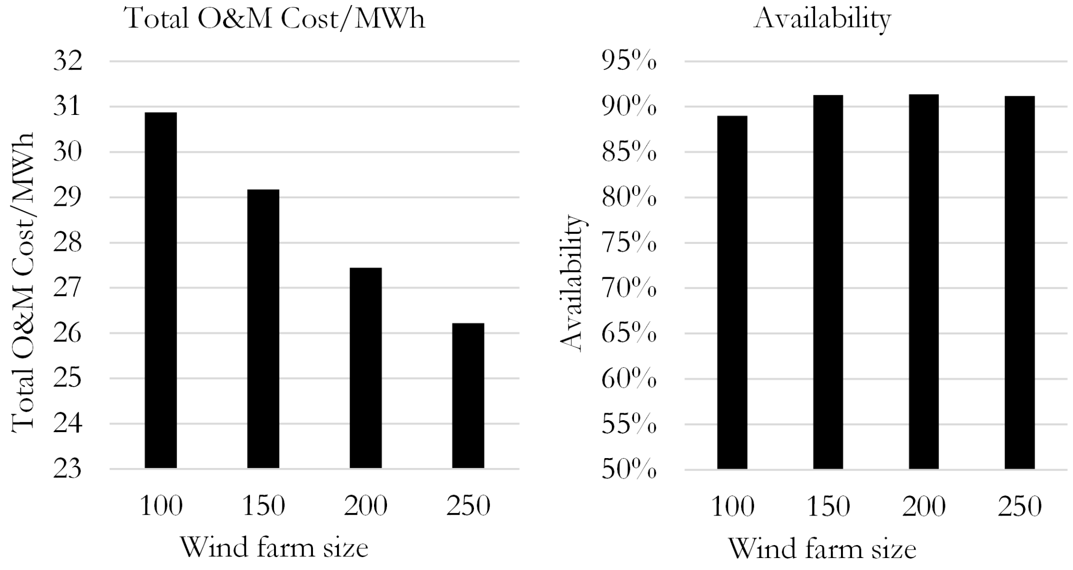

Figure 174: Total O&M cost/MWh and availability

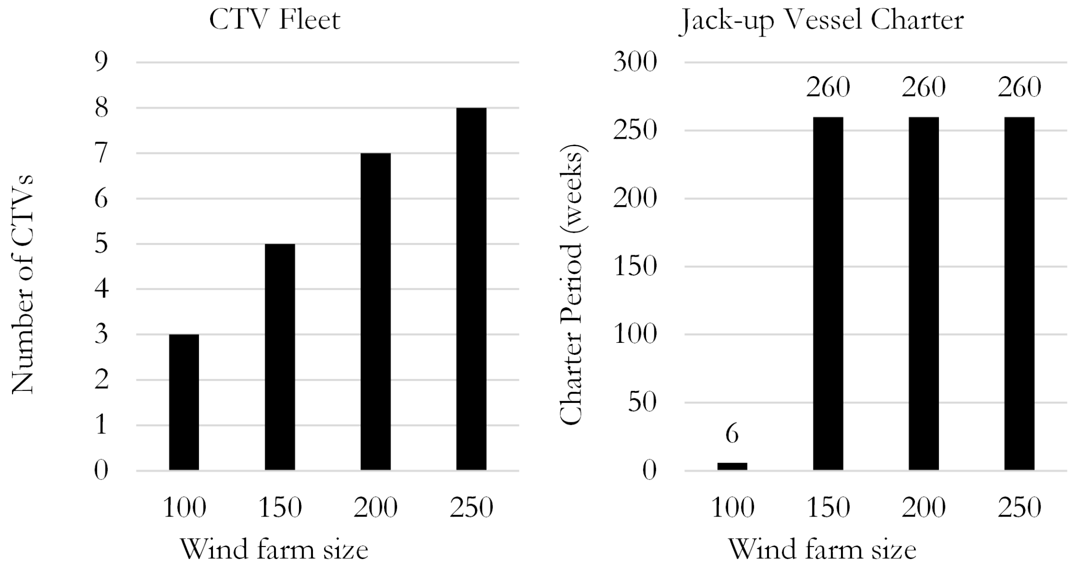

Figure 175: Size of CTV fleet and jack-up vessel charter period

Figure 176 and Figure 177 show the key results about the increase in the individual wind turbine power production capacity. Due to the fact that the size of the turbines is changed, the power curves and hub height values also need to be updated. The change in the hub height values affect the calculated wind speed values at hub level. The power curves and the turbine specifications for 5.0 MW, 6.15 MW and 10.0 MW turbines are provided by Staffell (2012), Goesswein (2010), Windtec Solutions (2012), respectively. The results of the power production capacity change show that a decrease in cost can be expected with the increase in the capacity. In this case, more power is produced by each turbine;

however, there is an associated increased turbine CAPEX cost, which should also be taken into account.

Due to the fact that the unit cost of keeping the larger turbines offline is higher than the cost of keeping the smaller turbines offline, the simulation logic increases the availability by improving the O&M fleet. As shown in Figure 177, the number of CTVs and the length of jack-up vessel charter increase by the improvement in the turbine capacity. In the base case, the CTV fleet is comprised of 3 CTVs. With the increase in the capacity, the number of CTVs is first increased to 4 and then 6. A similar trend can be observed in the jack-up vessel charter. The vessel is chartered for 6 weeks for the 3.6 MW and 5.0 MW turbines and then chartered long-term for the 6.15 MW and 10.0 MW turbines. By improving the O&M fleet, the average availability is increased by 2.6%.

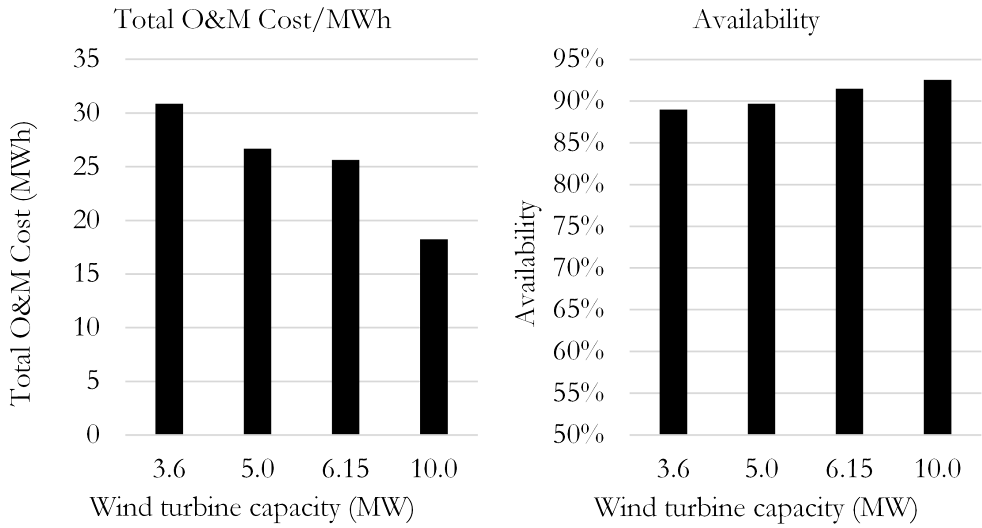

Figure 176: Total O&M cost/MWh and availability

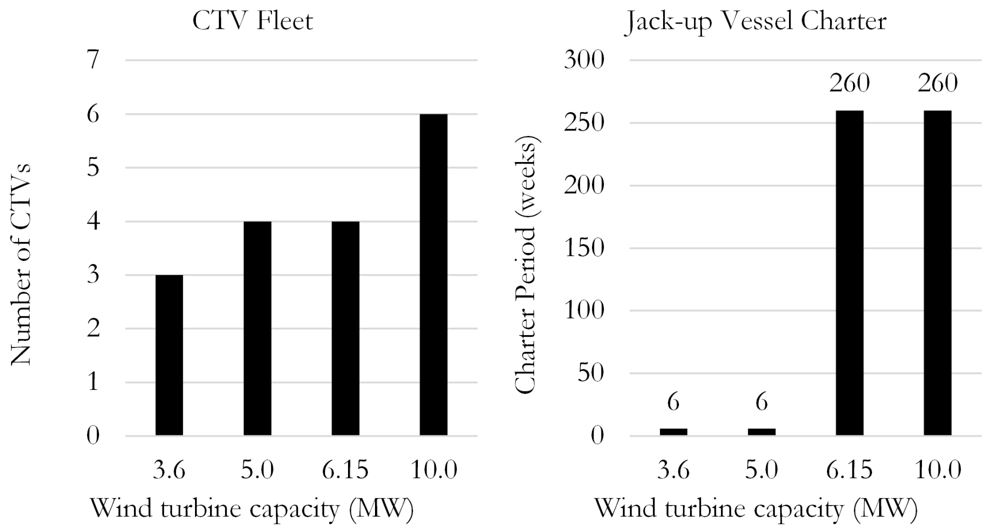

Figure 177: Size of CTV fleet and jack-up vessel charter period

7.7 Electricity price

In this analysis, the electricity price, which is £140/MWh in the base case, is altered. The majority of the inputs such as wind farm size, turbine capacity, distance are expected to increase in the forthcoming projects. On the other hand, the LCOE is expected to decrease. According to Kost *et al.* (2013), the LCOE from offshore wind resources is currently around £150. However, it is expected to be in the range of £100-£110 by 2030. In this context, the sensitivity analysis is performed by decreasing the electricity price instead of increasing it. In this respect, the electricity price is decreased from £150/MWh to £90/MWh with £10/MWh intervals. Figure 178 and Figure 179 show the change in the key aspects when the electricity price is decreased.

The electricity price has no direct influence on the direct O&M cost or on the power production; however, the revenue loss, which is proportion of the calculated revenue to the theoretical maximum revenue, is directly affected by the cost of electricity. In Figure 178, annual revenue decreases with the decrease in the electricity price. On the other hand, the O&M cost remains at the same level. Therefore, the proportion of the loss to the maximum revenue increases. The price change does not affect the size of the CTV fleet as shown in Figure 179. The jack-up vessel charter period decreases by the decrease in the electricity price.

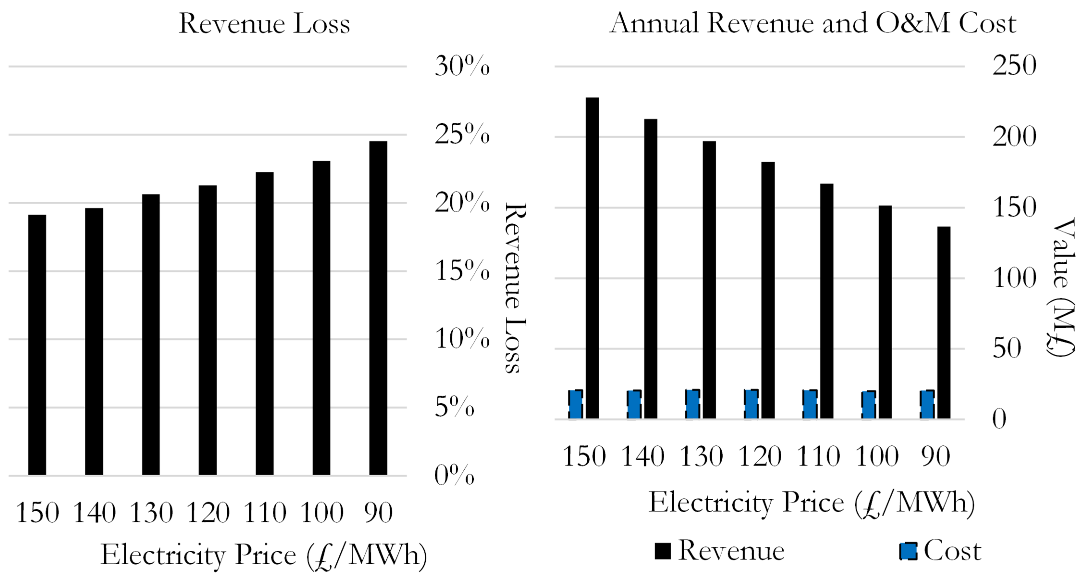

Figure 178: Revenue loss, annual revenue and annual O&M cost

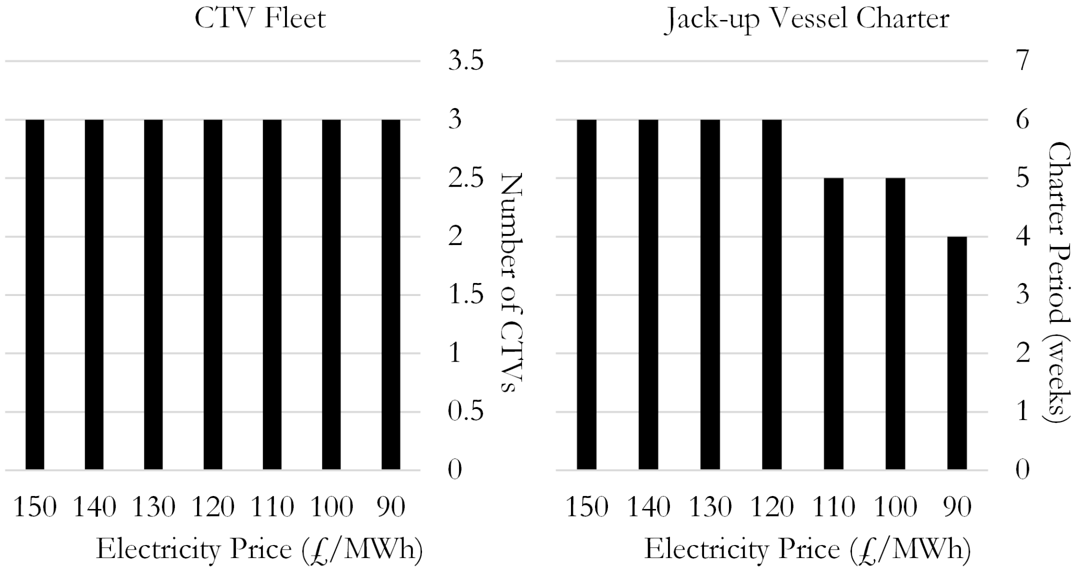

Figure 179: Size of CTV fleet and jack-up vessel charter period

7.8 Mobilisation period

Mobilisation period is an important aspect for the jack-up vessel operations; therefore, it is essential how the key aspects are affected by the change in the mobilisation period. In the base case scenario, the mobilisation period is defined as particular time periods and associated probability values. In order to demonstrate the influence of mobilisation period in a more clear way, the probability values associated with mobilisation periods are manipulated. In this respect, 10 different cases, in which the mobilisation period values are increased by one month, are simulated. Thus, the mobilisation period is defined as one month for the first case and similarly it is defined as ten months for the tenth case.

Figure 180 and Figure 181 show the results of the simulated cases. There is 4% decrease in the availability, which can be explained by the increase in the MTTR values of the major turbine components. The difference in the MTTR values is significant. There are 720 time-steps in one month, which implies that in each case the mobilisation period is increased by 720. This also implies that the turbines remain out of service for a longer period. An increase in MTTR values is expected; however, the level of increase is not equal to the increase in the mobilisation period. Essentially, when the mobilisation period is increased, the number of turbines that the jack-up vessel needs to visit also increases. Considering the fact that mobilisation period is applicable for the first failed turbine, the subsequent failures can be repaired in a relatively shorter period than the first failure. Thus, the average MTTR value decreases.

The increase in the mobilisation period has no direct influence on the size of the CTV fleet. On the other hand, there is a significant effect on the charter period of the jack-up vessel. An increase can be noticed in the jack-up vessel charter period with the increase in the mobilisation time. When the mobilisation period is defined as one month, 4-weeks jack-up charter is sufficient to complete all the major repairs in a cost effective way. On the contrary, when the mobilisation period is defined as 10 months, the jack-up vessel needs to be chartered 8 weeks. This is because, the turbines continue failing during mobilisation time and therefore the optimum jack-up vessel charter period increases by the increase in the mobilisation period.

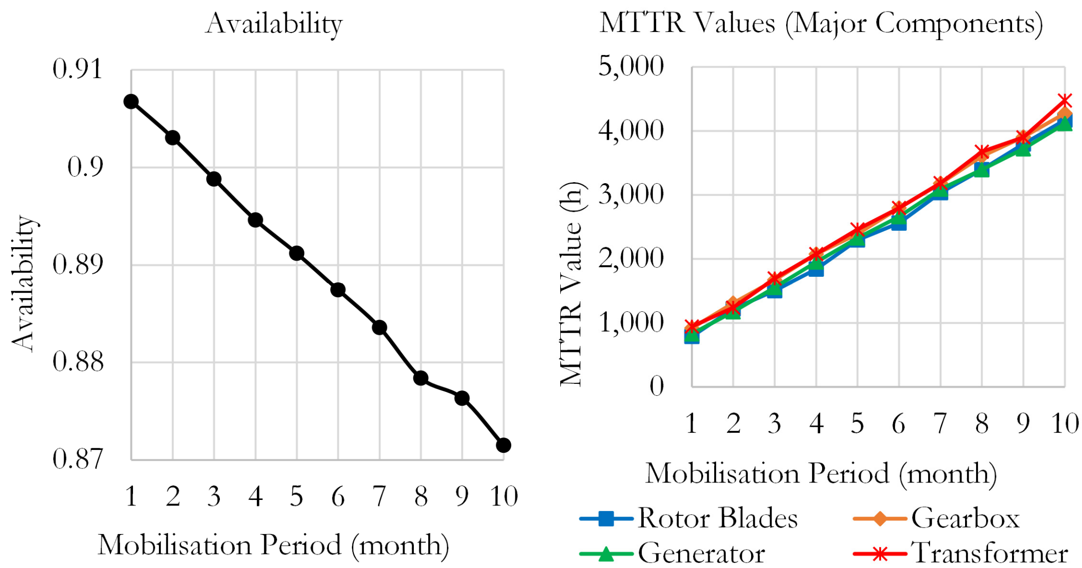

Figure 180: Wind farm availability and MTTR values

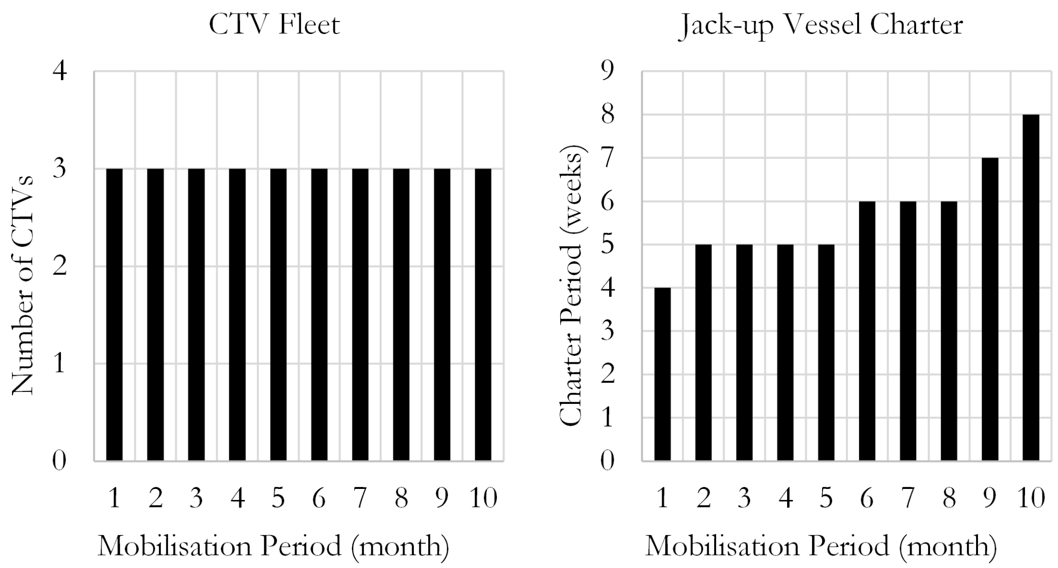

Figure 181: Size of CTV fleet and jack-up vessel charter period

7.9 CTV technicians shift start time

In this analysis, a potential improvement in the cost and availability is sought by altering the CTV technicians shift start time. In the base case configuration, the shift start time is defined as 8 a.m. Due to the fact that O&M activities limited by the daylight period, it is believed that an alteration in the shift start time can create an impact. In this respect, 6 a.m., 7 a.m., and 9 a.m. shift start values are simulated in addition to the 8 a.m. shift start value in the base case configuration. The results of this analysis are presented in Figure 182. It can be seen that an alteration in the shift start value changes the total O&M cost/MWh value and availability. This change is associated with using the day time in an effective way. 6 a.m. and 7 a.m. are identified as early to transfer technicians to the offshore wind farm location. Considering the fact that the length of a working shift is limited by 12 hours, transferring technicians early in the morning also results in completion of the working shift in an early time. On the contrary, transferring the O&M technicians at 9 a.m. is identified as late, because daylight cannot be used as efficient as when the technicians are transferred at 8 a.m.

It is noticed that the change in the simulations results are not as high as the changes in the previous sections. However, defining the shift start value is a straightforward decision and operators have full control on this aspect. Therefore, it can be beneficial for operators to explore their current operational practices. At this stage, it is also important highlight that the duration of daylight is dependent on the wind farm location and therefore, the result of this particular case can change, if the wind farm is installed in a different location.

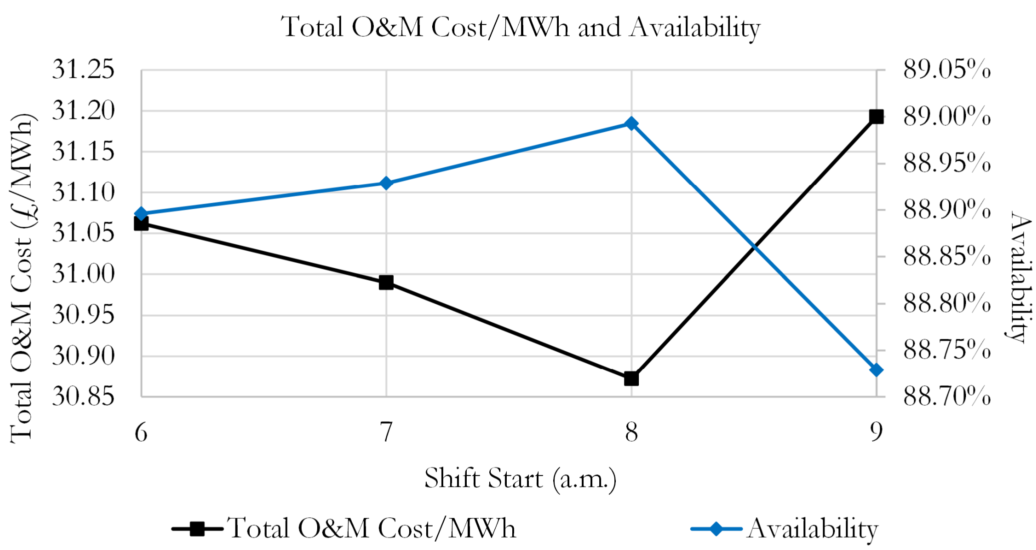

Figure 182: The impact of the shift start value

7.10 Chapter summary

In this chapter, a detailed sensitivity analysis is performed in order to present the performance of the developed model under different input configurations. In order to validate the model, the major aspects, which influence the O&M activities, are altered and operational simulation are performed. In this context, distance to O&M port, component aging and failure rates, vessel charter rates, wind farm size and individual turbine power production capacity, electricity price, jack-up vessel mobilisation period, and CTV technicians shift start time inputs are changed and associated simulation results are presented. In general, reasonable results are observed. It is also shown that each offshore wind farm case has particular characteristics, which significantly influence the direction of the decision. Therefore, generalisation in final decisions is not an easy task to achieve. It is believed that similar operational simulations need to be performed in order to make reliable decisions.

7.11 References

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8 Discussion and Recommendations for Future Work

8.1 Achievement of the research objectives

The purpose of this research is to contribute theoretically and empirically to the offshore wind operation and maintenance topic. The comprehensive material in this study makes empirical contribution by improving the knowledge in fields of offshore wind O&M practice, and O&M vessels with a focus of comprehensive maintenance planning. At this stage it is important to highlight the objectives initially explained in chapter 3 and discuss the progress to achieve these research objectives.

Research Objective 1. Identify the gaps in the literature and issues in the offshore wind operation and maintenance sector. Perform a thorough critical review. Identify the focus of research, for which an improvement can create the largest impact on the operational phase of offshore wind farms

This objective is achieved by investigating the existing maintenance methodologies and approaches in the literature already applied in the offshore wind O&M sector and similar industries. Practical and contextual issues in the sector are also examined. Furthermore, current O&M models are explored in depth in order to identify how accurately offshore wind O&M is modelled. Through detailed analysis, the need for an enhanced O&M model, which considers vessel associated aspects in a comprehensive way, has been established. A major gap is identified in the field of transportation systems associated with the O&M activities. Although the cost of transportation systems account for more than 50% of the overall O&M cost, the offshore access related operations are generally overly simplified or modelled in a crude way. Therefore, a better understanding about the usage of different transportation systems is required.

Research Objective 2. Propose a methodology to address the focus of research identified, considering operating wind farms as well as forthcoming projects

This is achieved by proposing and establishing the comprehensive operational expenditure model for the offshore wind O&M industry in chapter 4. The developed model consists of climate generation, vessel operability and transit time, failure simulation, repair simulation, power calculation, and cost calculation blocks. These aspects have never been examined in a single framework while considering the interdependency of each parameter in the overall offshore wind sector before. Offshore wind farm operators can perform analysis by using the developed model to investigate the most favourable O&M

fleet, which leads to significant cost reductions. The model is comprehensive enough to represent wind farms in operation as well as forthcoming projects. It is important to propose a model, which can address the issues currently experienced by the industry; it is also important to have flexibility to simulate forthcoming project. These two strong points can assist offshore wind farm operators in operational stage as well as in early planning stage of future wind farm projects.

Research Objective 3. Demonstrate the application of the methodology and identify the key parameters that influence operational and financial decisions. Elaborate the decisions associated with the configuration of operation and maintenance fleets

The developed model has been tested against two different offshore wind farm cases in chapter 5 and chapter 6. These two case studies show the developed model is working accurately not only for operating wind farms but also for future projects. The result of these cases studies are discussed with the offshore wind sector representatives in fortnightly online meetings and workshops (once every six months). The majority of the operational aspects are quantified and demonstrated to the reader. The principal aim of the model is to improve the knowledge of transportation systems utilised in offshore wind O&M sector. Therefore, vessel associated case studies are performed and the results are demonstrated.

In the first case study, a comprehensive study has been performed in order to identify the most favourable O&M fleet for an operating wind farm in the UK. It is concluded that CTVs with higher operational capabilities bring significant financial and operational advantages to offshore wind O&M activities. Although, CTVs with higher operational capabilities associated with higher operational costs, the increase in power production can compensate the increase in direct O&M cost. A smaller O&M fleet can be sufficient to sustain power production, if advanced CTV types are taken into account. A smaller O&M fleet also leads to reduced operational and financial risks. Based on the case study results, 6-weeks jack-up vessel charter is identified as the most favourable alternative in order to optimise the operational costs. Among major cost aspects, the level of revenue loss is identified as the key aspect that influence the size of O&M fleet and the decision related to jack-up vessel charter period. The vessel charter cost is identified as the largest cost contributor among the direct O&M cost aspects. The highest power production does not lead to the lowest operational costs, because there is an optimum power production level, which results in minimised operational costs. In order to achieve a power production value higher than the optimum level, an investment, which results in a higher cost than the financial benefit, is required.

The second farm is envisaged as a potential future project as the industrial trends indicate that the future wind farms will go further and deeper offshore. In this case study, two mothership concepts are explored for a wind farm located in far offshore. It is identified that wind farm accessibility drops significantly by an increase in distance. Therefore, the decision of considering a mothership in the O&M fleet becomes inevitable for far offshore locations. Based on the case study results, the floating hotel mothership concept is identified as a better alternative over the pro-active mothership concept. The daughter crafts on the pro-active mothership concept do not bring a considerable advantage to the operations, because operational capabilities of the daughter crafts are significantly low. Therefore, these crafts are rarely utilised in the operations. The selection of the charter period is related to charter rate the mothership. For lower daily charter rates, a continuous mothership charter can be considered. On the other hand, for higher daily charter rates, a seasonal mothership charter has to be considered. The October-March period is identified as the most critical season for mothership charter, because wind farm accessibility is significantly limited in this period. Thus, maximum benefit can be observed by chartering the mothership in the October-March period.

Research Objective 4. Validate the methodology and demonstrate the performance of the methodology under different circumstances

A sensitivity study has been performed in chapter 7 in order to validate the developed model and also demonstrate the performance of the model under different financial and operational circumstances. In this context, the distance to O&M port, age of components and failure rates, CTV and jack-up vessel charter rates, wind farm size and individual turbine capacity, electricity price, jack-up vessel mobilisation period, and shift start time of O&M technicians are altered. These aspects are analysed in depth for the first time. By investigating the change in distance, shift start time, wind farm size and turbine capacity, the aspects that operators have a certain level of control are analysed. The O&M cost/MWh and availability values are demonstrated with respect to each aspect analysed in order to assist operators towards optimised cost and availability. Operators do not or have a limited control on the component failure rates, vessel charter rates, electricity price and jack-up vessel mobilisation period. Therefore, it is not straightforward for operators to take direct action on these aspects. On the other hand, it is important to quantify the risks, which operators can face within 25-years of operational life span. The results of the sensitivity analysis are found accurate within the facts and prospects of the offshore wind O&M industry.

Research Objective 5. Provide suggestions at both generic and detailed level on how to improve the reliability of the offshore wind O&M activities, define a favourable operation and maintenance fleet (size and operational capability) and reduce the wind farm operating costs

This objective is achieved by interpreting the analysis results demonstrated in chapter 5, 6 and 7. CTVs with higher operational capabilities are identified as a favourable alternative over CTVs with lower operational capabilities. Even a larger CTV fleet cannot guarantee a low O&M cost/MWh, if the fleet comprises CTVs with lower operational capabilities. The short-term jack-up vessel charter is suggested for currently operating wind farms, which the size and power production level are not as high as forthcoming projects. When the number of turbines in the wind farm or the power production capacity of the turbines are increased, the long-term charter option becomes more cost effective than the short-term charter option. This result is associated with the cost of keeping the turbines in failed condition. The long-term jack-up vessel charter is also identified as a favourable option, when the age or failure rate of the turbine component increase. Jack-up vessel mobilisation is identified as the most critical aspect that affects the major component MTTR values. An increase in the distance to O&M port result in an increase in the CTV fleet. Regardless of the improvements in the O&M fleet, the O&M cost/MWh keeps increasing by the increase in the distance. It is also suggested that each wind farm case has to be analysed individually, because a broad generalisation, which covers all the possible cases, cannot be made due to high number of variables.

8.2 Recommendations for future research

Despite the decent improvements in the offshore wind O&M sector, there are still a large number of areas, where future research opportunities exist. The majority of these research areas can directly improve the scope of this thesis. On the other hand, there are also particular areas, for which detailed and more accurate information is required. The following categories are identified as the key research topics for future research;

- Due to the seasonality in climate parameters, it is believed that seasonal changes in O&M fleets also need to be considered such as considering a larger fleet in winter and a smaller fleet in summer (or the opposite).
- There is a great potential to decrease the costs, especially jack-up vessel associated costs by considering the 'jack-up vessel club' concept, which is based on the vessel sharing by multiple operators. Although it is a great potential, the club concept need to be improved in order to address the industry concerns.
- From simulation logic point of view, development of an optimisation algorithm can be beneficial in order to improve the computation time. The optimisation algorithm can be an efficient way to eliminate unnecessary configurations, which are far from optimised level.
- Due to the fact that the operating costs are significantly high, the cost reduction has always been the first priority to make renewable energy competitive. However, it is believed that the risks associated can be overlooked, if the overall framework is not taken into account. It should be highlighted that both financial and operational risks are expected to be higher in the future. Therefore, a decision support mechanism, which considers costs but also other aspects from a systems point of view such as risk and safety can be useful for the industry.
- O&M activities are not performed during night. This creates a large impact on the power production and operational costs. In this research, it is identified that the cost of vessels has the highest share in the operational costs. By performing the operations 24 hours-365 days, O&M vessels can be utilised more efficiently and significant cost reductions can be achieved. A research study, which technically makes O&M tasks possible to be performed during day and night, can be an excellent opportunity for the offshore wind O&M sector.
- In general, data is not easily accessible even not available in the public domain. Failure rates, vessel charter rates, cost of components are rarely accessible, which limits the accuracy of the developed models. It has been identified that in some cases, even offshore wind farm operators do not have access to data due to high number of parties involved in the operations. Therefore, future studies have to prove how important it is to have reliable data. At the same time, it is also

important to develop models, for which operators have available data to perform analysis.

- The impact of climate on failure rates needs to be investigated in depth
- Advanced O&M models for very large offshore wind farms (>500 turbines) need to be developed. For instance the majority of the developed models consider a single jack-up vessel; however, two or more vessels can be required for very large offshore wind farms.

9 Conclusions

9.1 Novelty of the research

The novelty of this research comes from both the developed O&M model, its structure and the analysis that can be performed by the model. There is a knowledge gap in the area of offshore wind O&M and particularly about vessels, their usage and associated costs. In this respect, this research study addresses this gap in knowledge by developing a detailed operational expenditure model and investigating optimum O&M vessel fleet for offshore wind farms. A detailed vessel transit model, which considers difference vessel types and major operational limitations, is developed for the first time within the offshore wind sector. A jack-up vessel charter rate estimation algorithm for different chartering strategies is introduced. Different cost aspects associated with alternative jack-up vessel chartering strategies are demonstrated in an offshore wind OPEX model for the first time. The integration of climate parameters, vessel specifications and wind farm characteristics (capacity and failures) are integrated into a single framework for the first time. In addition to the primary output, the secondary outputs will fully demonstrate the underlying relations between variables and cost drivers. In the future, advance O&M strategies will need to be implemented. Therefore, a better understanding associated with the variables and their influence on the offshore wind O&M and wind farm productivity is required. Identification of the areas, which primarily need to be developed, is crucial to reduce operational costs.

The model integrates a number of calculation blocks; therefore, the model structure allows implementation of more advanced modules in the future without creating a brand new model. It is well known that each operator has its own operational culture and safety rules; therefore, the model can easily be modified in accordance with the company requirements. It is identified that the majority of the studies in the literature only focus on a single aspect such as climate, failures or availability. This research considered all the major aspects in the operational scope. The detail of the modelling surpasses all the offshore wind O&M studies currently available. The uncertainty in climate, failure and cost aspects are considered in a comprehensive manner. It is believed that this research will support the industry to achieve its cost reduction targets.

9.2 Contributions of the thesis

9.2.1 Contribution to theory

This thesis has presented an offshore wind operational expenditure model that enables the lifetime operational costs of offshore wind to be calculated. In particular, a novel framework has been developed, in which artificial neural networks, Monte-Carlo simulations and comprehensive transportation and repair examination process have been integrated. Representative wind speed, wave height and wave period datasets are generated by using neural networks. Furthermore, vessel operability and accessibility are examined in depth. A transit time model for crew transfer vessels is implemented in the operational simulations. In addition, different crew transfer vessels are examined from operational and financial points of view. A jack-up vessel charter rate estimation procedure for different chartering strategies has been introduced to the offshore wind industry. The developed model can be used to validate the future models.

9.2.2 Contribution to practice

The model enables to examine different crew transfer vessels, which can have different operational characteristics. Offshore wind farm operators can perform cost-benefit analysis by using the develop model in the crew transfer vessel selection stage. Due to the fact that offshore wind farm operators may not have access to specific vessel information such as hull form, the model has been established to require accessible information. The jack-up vessel charter rate estimation procedure can assist operators in calculating the variability that they can experience in operational life span of an offshore wind farm. Moreover, the analysis improves the understanding of cost distribution under different operational configurations. This model improves the reliability of decisions and allow operators to recognise the consequence of operating decisions in a new level of detail. The model also assist the operators in making best decisions and planning as far as cost effective wind farm operations are concerned.

9.3 Concluding remarks

In this thesis, a novel operational expenditure model for offshore wind farms has been introduced and an optimum O&M fleet investigation study has been performed. Overall, the concluding remarks of this research study are presented in the following statements;

1. A CTV with better capability brings great financial and operational advantages, even though that CTV has higher daily OPEX cost. Increasing the size of the CTV fleet does not always bring an economic advantage due to the fact that the cost increase cannot be compensated by the production increase if the CTV fleet becomes larger than the optimum level. The capability and operational limitations of the CTVs are also important attributes which significantly influence the fleet size.
2. Mothership can improve the performance of the offshore wind farms noticeably, since these assets minimise the transit time between offshore wind farm and O&M port, and therefore maximise the productive period in a working shift. In far offshore locations, conventional O&M strategies performed by conventional O&M vessels will not be cost-effective. Therefore, offshore wind operators will need to consider a mothership in their O&M fleets.
3. Although the operational risks increase by performing O&M activities during night, the achievements cannot be disregarded. It should be highlighted that the current operational practices and regulations strictly (especially in the UK) limit the access to turbines by daylight; however, if the offshore wind industry identifies the financial and operational benefits of the night shift, advanced technologies can be developed. In addition, when the mothership designs become mature, which provides 24 hour access in a relatively short distance, it is believed that continuous O&M activities will increase the power productivity and decrease the costs.
4. The cost of jack-up vessel related operations is significantly higher than any other transportation system in the O&M fleet. Therefore, the jack-up vessel charter period has to be investigated carefully, before chartering the jack-up vessel.
5. As the number of turbines in offshore wind projects increases, and the wind farms are located further away from shore, there is a need to develop specialised new O&M vessels and transfer systems that will provide access to turbines throughout

the year in rough sea conditions. New approaches may involve moving from port-based operations to ship-based strategies.

6. There is great advantage to hire the vessels for longer periods of time. However, there are also some investment risks, which operators have to bear in mind. These risks can be mitigated through sophisticated maintenance approaches and more accurate planning. In this respect, a separate management team, which is responsible from only vessel management, has to be utilized by the companies in order to keep the vessel operating.
7. Today's jack-up vessels have approximately 65 m operational water depth limit. In the future, jack-up vessels will not be sufficient for the maintenance operations due to the extreme depths. If designers/developers do not design/build floating offshore wind turbine maintenance vessels, the dependency to the offshore oil and gas industry will sustain and thus charter rates will continue to be determined by external players.
8. The jack-up operations cause significant delays mainly due to jack-up mobilisation time. In this respect, chartering the vessel for the entire project lifecycle could be a solution, which would eliminate or minimise the mobilisation time. However, chartering the vessel for a long period increases the total O&M cost and eventually the total financial loss drastically. Especially for the small wind farms, chartering a jack-up vessel for the entire project lifecycle is not feasible, considering the fact that vessel owners request considerably higher charter rates and expect high profits as in the offshore oil and gas industry. On the other hand, long-term chartering and purchasing options can be feasible for the next generation larger sites in the UK, Germany and Denmark. In this respect, regional collaborations between different operating companies, which should also be supported by national and international legislation, can be the solution towards optimised jack-up vessel cost and maximised utilisation throughout the chartered period.

10 Appendix A

Table 47: Distribution parameters

Distribution name	Parameter name			Parameter description		
Generalised extreme value	k	sigma	mu	shape	scale	location
Log-logistic	mu	sigma	-	location	scale	-
t Location-Scale	mu	sigma	nu	location	scale	deg. of freedom
Log-normal	mu	sigma	-	location	scale	-
Inverse Gaussian	mu	lambda	-	scale	shape	-
Birnbaum-Saunders	beta	gamma	-	scale	shape	-
Gamma	a	b	-	shape	scale	-
Weibull	A	B	-	scale	shape	-
Exponential	mu	-	-	mean	-	-
Logistic	mu	sigma	-	location	scale	-
Nakagami	mu	omega	-	shape	scale	-
Rayleigh	B	-	-	scale	-	-
Rician	s	sigma	-	non-centrality	scale	-
Normal	mu	sigma	-	location	scale	-
Extreme value	mu	sigma	-	location	scale	-

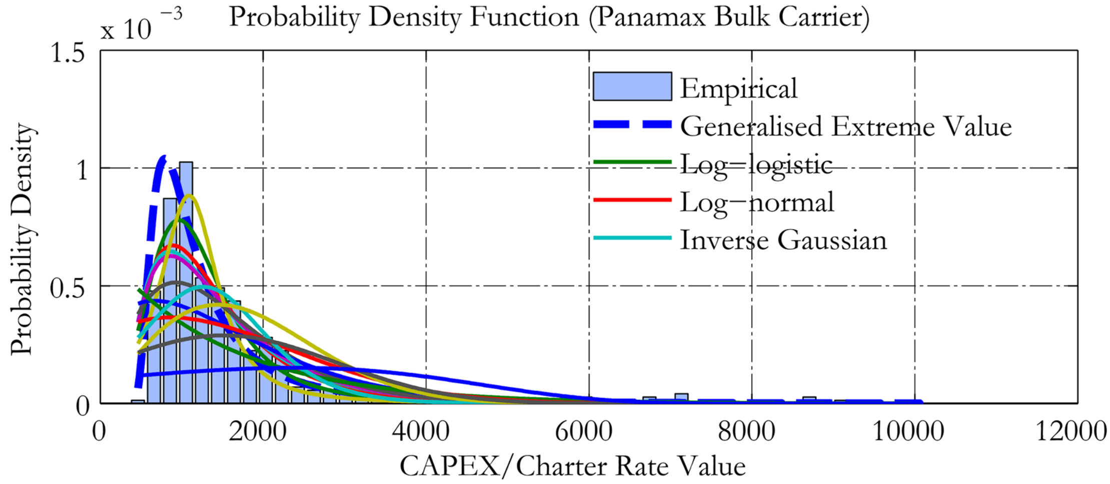


Figure 183: Panamax bulk carrier CAPEX/Spot market charter rate distributions

Table 48: Panamax bulk carrier CAPEX/Spot charter rate distribution rankings

Distribution name	AICC	Parameter		
Generalised extreme value	5716.58	0.50	394.98	941.75
Log-logistic	5774.87	7.06	0.30	-
Log-normal	5802.69	7.12	0.57	-
Inverse Gaussian	5808.41	1512.11	3780.22	-
Birnbaum-Saunders	5823.75	1283.21	0.61	-
t Location-Scale	5872.51	1090.07	390.06	1.62
Gamma	5918.27	2.58	585.74	-
Weibull	5990.57	1682.13	1.38	-
Exponential	6059.89	1512.11	-	-
Nakagami	6072.50	0.61	4178876.90	-
Logistic	6074.78	1262.81	504.10	-
Rayleigh	6144.26	1445.49	-	-
Rician	6146.29	62.34	1444.97	-
Normal	6298.05	1512.11	1377.54	-
Extreme value	6664.61	2379.31	2417.26	-

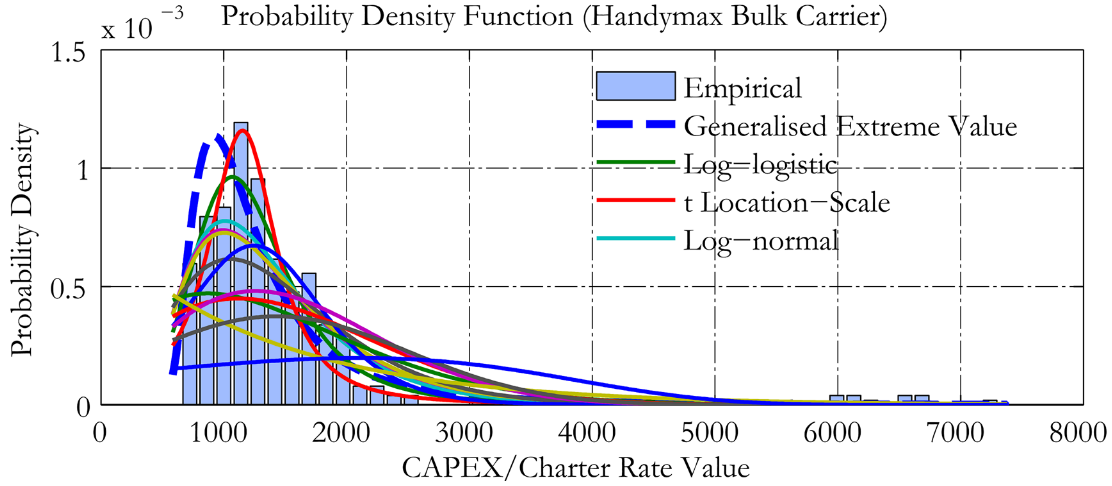


Figure 184: Handymax bulk carrier CAPEX/Spot market charter rate distributions

Table 49: Handymax bulk carrier CAPEX/Spot charter rate distribution rankings

Distribution name	AICC		Parameter	
Generalised extreme value	5555.80	0.36	343.31	1019.80
Log-logistic	5597.89	7.08	0.23	-
t Location-Scale	5643.10	1152.92	300.53	1.76
Log-normal	5655.68	7.13	0.46	-
Inverse Gaussian	5669.57	1429.20	5747.14	-
Birnbaum-Saunders	5680.59	1281.45	0.48	-
Gamma	5771.35	3.81	375.61	-
Logistic	5860.84	1243.92	371.45	-
Weibull	5881.60	1614.20	1.60	-
Nakagami	5927.99	0.83	3175832.41	-
Rayleigh	5935.35	1260.13	-	-
Rician	5937.37	49.67	1259.75	-
Exponential	6018.84	1429.20	-	-
Normal	6111.39	1429.20	1065.99	-
Extreme value	6475.53	2105.16	1853.18	-

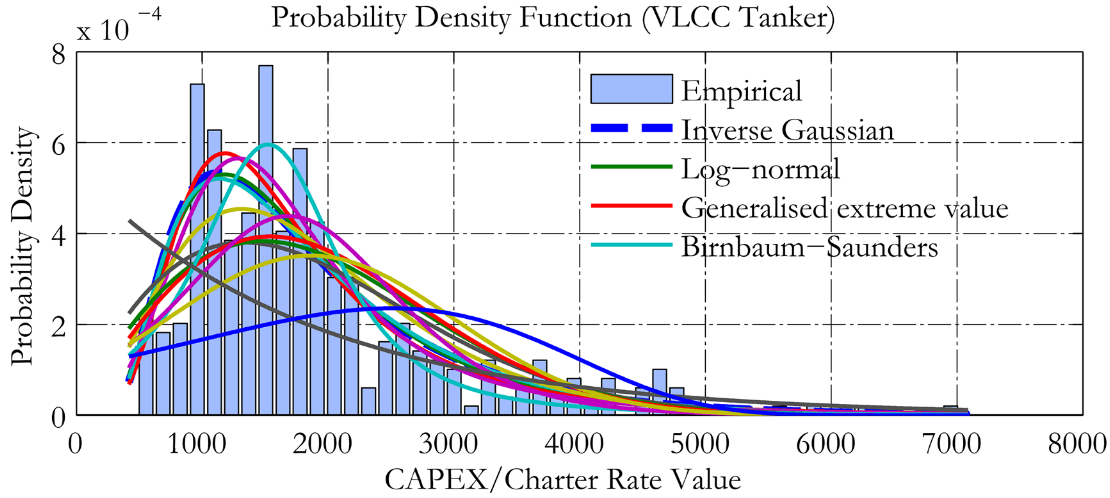


Figure 185: VLCC tanker CAPEX/Spot market charter rate distributions

Table 50: VLCC tanker CAPEX/Spot charter rate distribution rankings

Distribution name	AICC		Parameter	
Inverse Gaussian	5966.92	1861.50	5323.44	-
Log-normal	5967.85	7.37	0.55	-
Generalised extreme value	5968.26	0.22	653.24	1309.70
Birnbaum-Saunders	5968.49	1603.09	0.57	-
Log-logistic	5971.81	7.36	0.31	-
Gamma	5996.72	3.39	548.90	-
Weibull	6041.12	2108.42	1.79	-
Rayleigh	6048.73	1541.06	-	-
Nakagami	6049.55	0.93	4749720.69	-
Rician	6050.75	103.34	1539.64	-
t Location-Scale	6070.11	1523.87	595.93	2.08
Logistic	6105.62	1685.11	570.15	-
Normal	6157.02	1861.50	1134.94	-
Exponential	6211.22	1861.50	-	-
Extreme value	6384.91	2504.16	1561.42	-

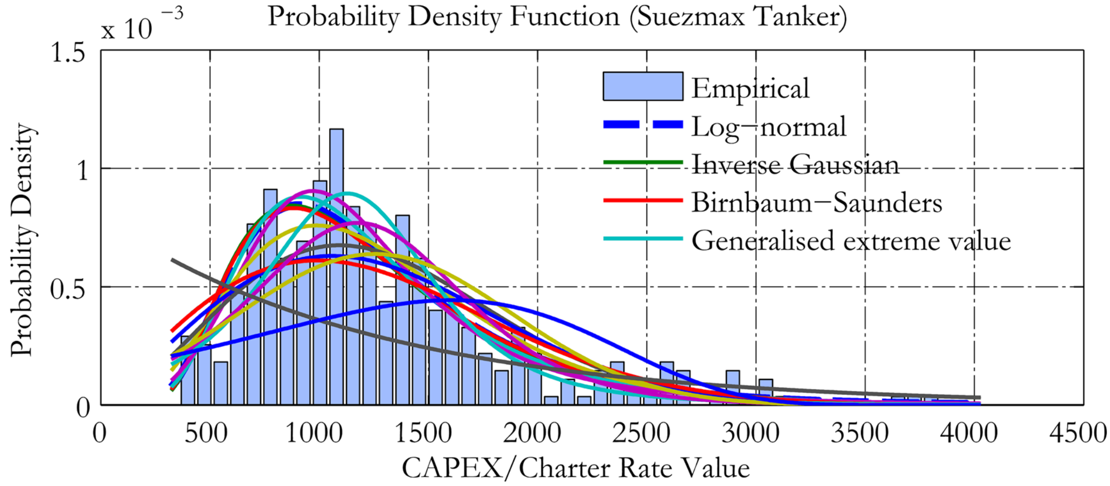


Figure 186: Suezmax tanker CAPEX/Spot market charter rate distributions

Table 51: Suezmax tanker CAPEX/Spot charter rate distribution rankings

Distribution name	AICC	Parameter		
Log-normal	5598.82	7.03	0.47	-
Inverse Gaussian	5599.37	1256.44	5135.97	-
Birnbaum-Saunders	5599.58	1126.27	0.48	-
Generalised extreme value	5600.93	0.11	420.63	961.80
Log-logistic	5602.12	7.02	0.26	-
Gamma	5614.07	4.70	267.13	-
Nakagami	5650.61	1.28	1968131.55	-
Weibull	5660.09	1424.11	2.14	-
Rayleigh	5661.09	992.00	-	-
Rician	5663.11	90.95	990.15	-
t Location-Scale	5674.07	1128.05	412.08	3.07
Logistic	5685.72	1177.03	324.78	-
Normal	5722.64	1256.44	624.94	-
Exponential	5925.05	1256.44	-	-
Extreme value	5930.45	1604.65	829.62	-

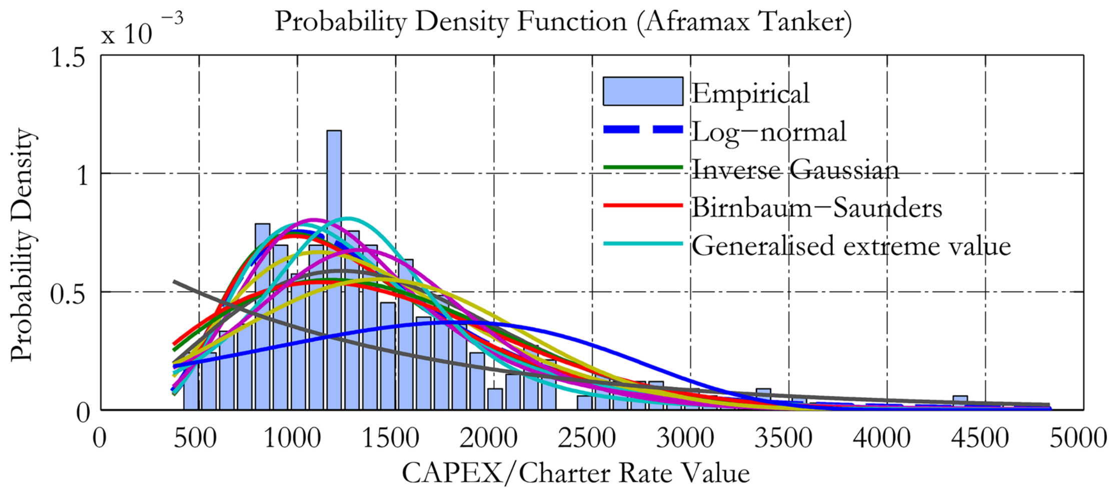


Figure 187: Aframax tanker CAPEX/Spot market charter rate distributions

Table 52: Aframax tanker CAPEX/Spot charter rate distribution rankings

Distribution name	AICC	Parameter		
Log-normal	5689.63	7.14	0.47	-
Inverse Gaussian	5690.33	1413.80	5646.67	-
Birnbaum-Saunders	5690.86	1264.49	0.49	-
Generalised extreme value	5690.95	0.13	472.23	1074.53
Log-logistic	5691.53	7.14	0.27	-
Gamma	5708.20	4.58	308.78	-
Nakagami	5749.48	1.23	2518202.03	-
Rayleigh	5756.87	1122.10	-	-
Weibull	5757.65	1602.75	2.09	-
Rician	5758.90	87.80	1120.62	-
t Location-Scale	5765.44	1254.74	451.85	2.81
Logistic	5782.62	1318.65	369.51	-
Normal	5827.40	1413.80	721.67	-
Exponential	6010.95	1413.80	-	-
Extreme value	6051.93	1819.23	990.53	-

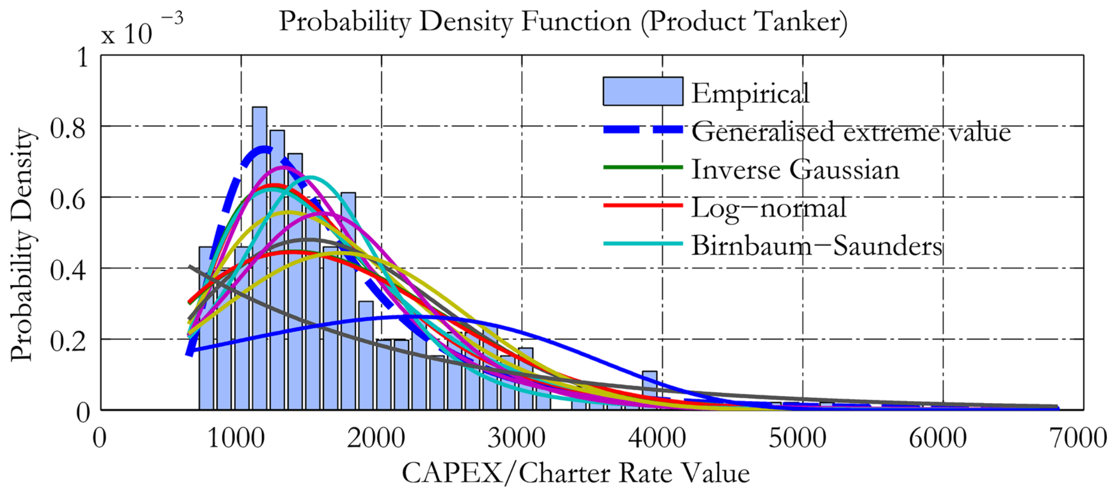


Figure 188: Product tanker CAPEX/Spot market charter rate distributions

Table 53: Product tanker CAPEX/Spot charter rate distribution rankings

Distribution name	AICC		Parameter	
Generalised extreme value	5796.03	0.23	513.71	1267.30
Inverse Gaussian	5802.32	1704.47	7315.93	-
Log-normal	5804.16	7.33	0.46	-
Birnbaum-Saunders	5804.65	1535.73	0.47	-
Log-logistic	5812.18	7.31	0.26	-
Gamma	5839.27	4.65	366.17	-
Nakagami	5896.87	1.21	3715232.16	-
Rayleigh	5902.48	1362.94	-	-
Weibull	5904.43	1932.44	2.02	-
Rician	5904.50	102.16	1361.36	-
t Location-Scale	5906.50	1492.20	560.49	2.98
Logistic	5926.74	1579.61	451.34	-
Normal	5989.17	1704.47	901.25	-
Exponential	6147.07	1704.47	-	-
Extreme value	6275.10	2224.04	1397.23	-

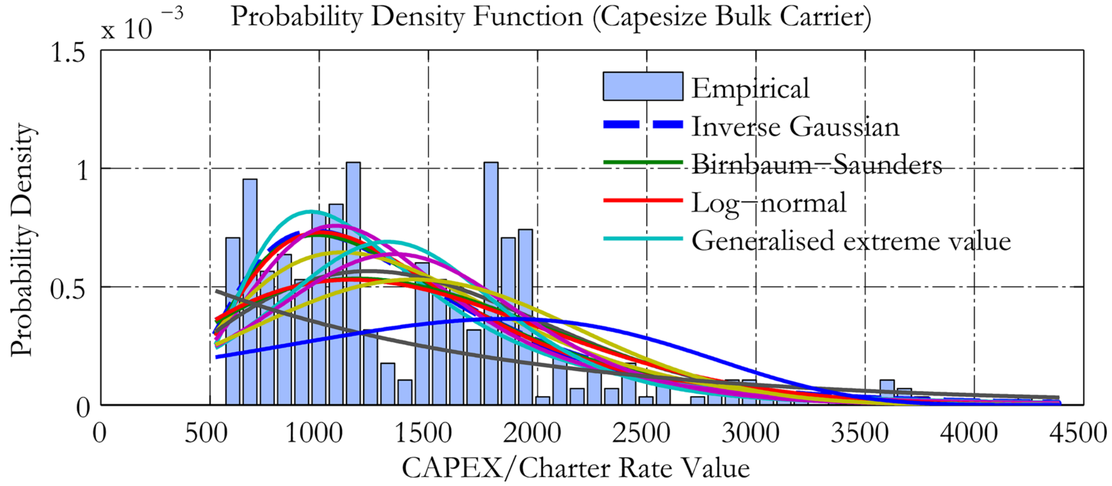


Figure 189: Capesize bulk carrier CAPEX/Time charter rate distributions

Table 54: Capesize bulk carrier CAPEX/Time charter rate distribution rankings

Distribution name	AICC	Parameter		
Inverse Gaussian	5706.02	1434.27	5545.75	-
Birnbaum-Saunders	5707.22	1278.86	0.49	-
Log-normal	5710.16	7.15	0.48	-
Generalised extreme value	5713.33	0.22	461.11	1053.56
Log-logistic	5727.72	7.14	0.28	-
Gamma	5733.84	4.36	329.32	-
Nakagami	5775.80	1.18	2620334.57	-
Rayleigh	5779.73	1144.63	-	-
Weibull	5781.44	1626.99	2.04	-
Rician	5781.76	92.92	1143.02	-
t Location-Scale	5809.11	1313.89	544.66	4.16
Logistic	5817.13	1346.44	391.90	-
Normal	5856.90	1434.27	751.51	-
Exponential	6021.41	1434.27	-	-
Extreme value	6071.63	1856.16	1008.59	-

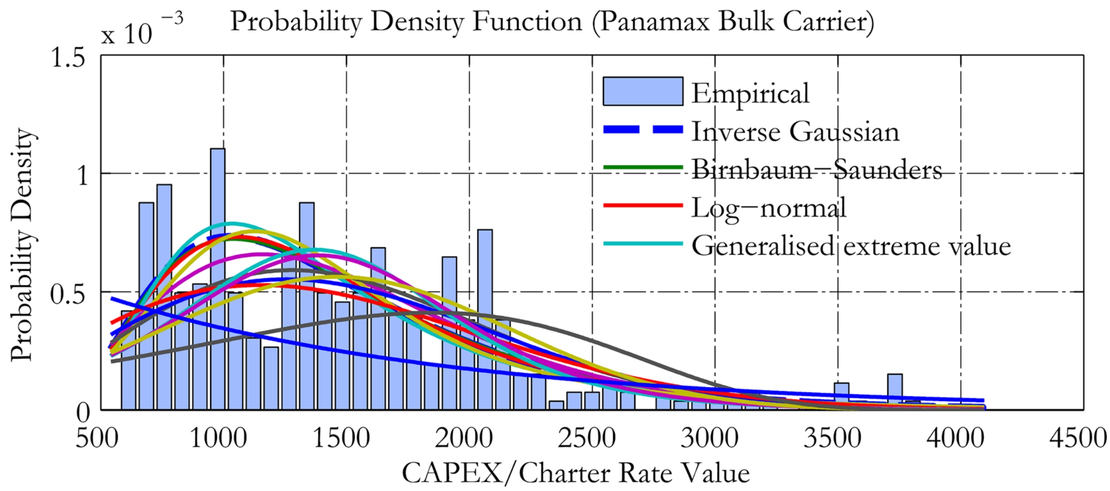


Figure 190: Panamax bulk carrier CAPEX/Time charter rate distributions

Table 55: Panamax bulk carrier CAPEX/Time charter rate distribution rankings

Distribution name	AICC	Parameter		
Inverse Gaussian	5697.02	1460.66	6215.60	-
Birnbaum-Saunders	5697.45	1314.56	0.47	-
Log-normal	5701.18	7.18	0.46	-
Generalised extreme value	5707.99	0.16	473.04	1104.96
Gamma	5717.12	4.81	303.96	-
Log-logistic	5721.15	7.18	0.27	-
Nakagami	5748.20	1.32	2633944.92	-
Weibull	5758.08	1655.86	2.20	-
Rayleigh	5761.83	1147.59	-	-
Rician	5763.85	147.33	1143.18	-
t Location-Scale	5791.02	1369.90	561.53	5.29
Logistic	5792.13	1386.33	382.38	-
Normal	5813.86	1460.66	708.37	-
Extreme value	5996.30	1850.53	892.93	-
Exponential	6034.69	1460.66	-	-

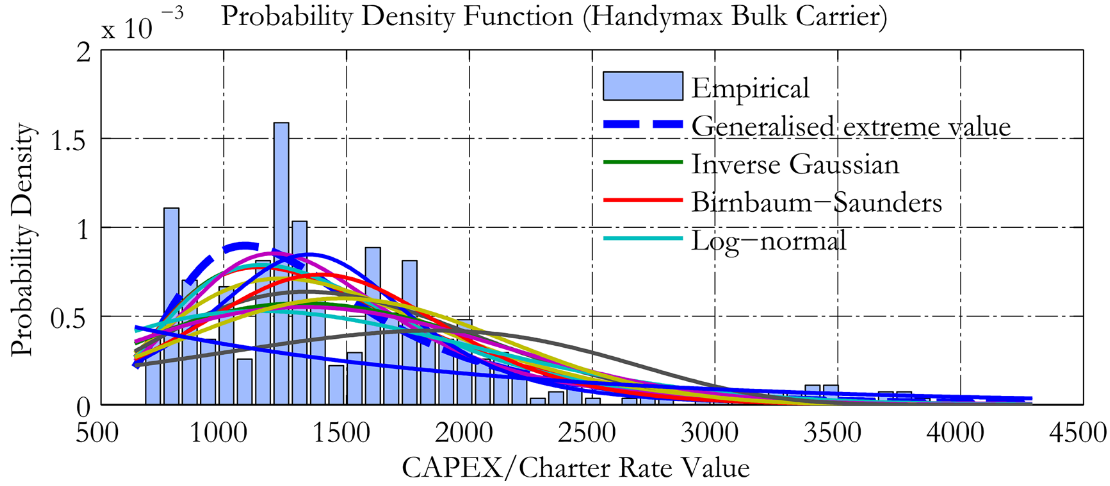


Figure 191: Handymax bulk carrier CAPEX/Time charter rate distributions

Table 56: Handymax bulk carrier CAPEX/Time charter rate distribution rankings

Distribution name	AICC		Parameter	
Generalised extreme value	5621.72	0.18	416.37	1155.48
Inverse Gaussian	5626.73	1480.30	8389.32	-
Birnbaum-Saunders	5628.18	1365.10	0.41	-
Log-normal	5628.51	7.21	0.40	-
Log-logistic	5635.59	7.20	0.23	-
Gamma	5656.15	6.02	246.02	-
Nakagami	5699.46	1.56	2632455.28	-
t Location-Scale	5707.60	1347.71	435.80	3.16
Weibull	5721.37	1674.53	2.34	-
Logistic	5723.33	1394.43	340.63	-
Rayleigh	5735.50	1147.27	-	-
Rician	5736.24	1123.79	827.53	-
Normal	5768.01	1480.30	665.13	-
Extreme value	5976.15	1854.15	878.01	-
Exponential	6044.41	1480.30	-	-

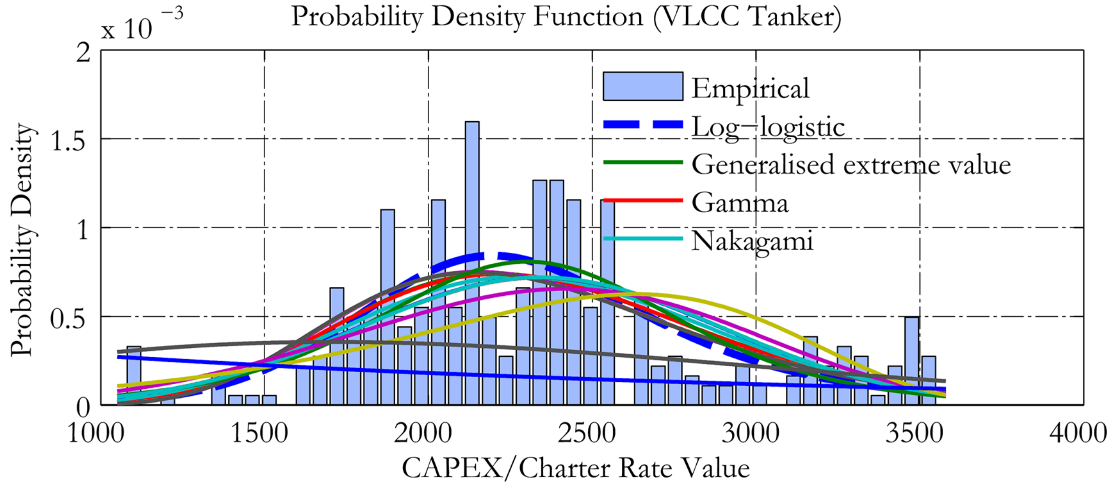


Figure 192: VLCC tanker CAPEX/Time charter rate distributions

Table 57: VLCC tanker CAPEX/Time charter rate distribution rankings

Distribution name	AICC	Parameter		
Log-logistic	5618.44	7.73	0.13	-
Generalised extreme value	5620.29	-0.16	503.55	2120.42
Gamma	5621.40	17.92	130.72	-
Nakagami	5625.13	4.67	5796005.67	-
Log-normal	5625.39	7.73	0.24	-
Birnbaum-Saunders	5626.78	2276.19	0.24	-
Inverse Gaussian	5627.00	2342.82	39459.66	-
Rician	5635.30	2271.72	563.60	-
Logistic	5636.05	2301.38	309.39	-
Normal	5636.24	2342.82	555.01	-
t Location-Scale	5638.27	2342.80	554.25	334843.23
Weibull	5655.95	2562.85	4.44	-
Extreme value	5733.66	2633.04	588.08	-
Rayleigh	5934.18	1702.35	-	-
Exponential	6378.64	2342.82	-	-

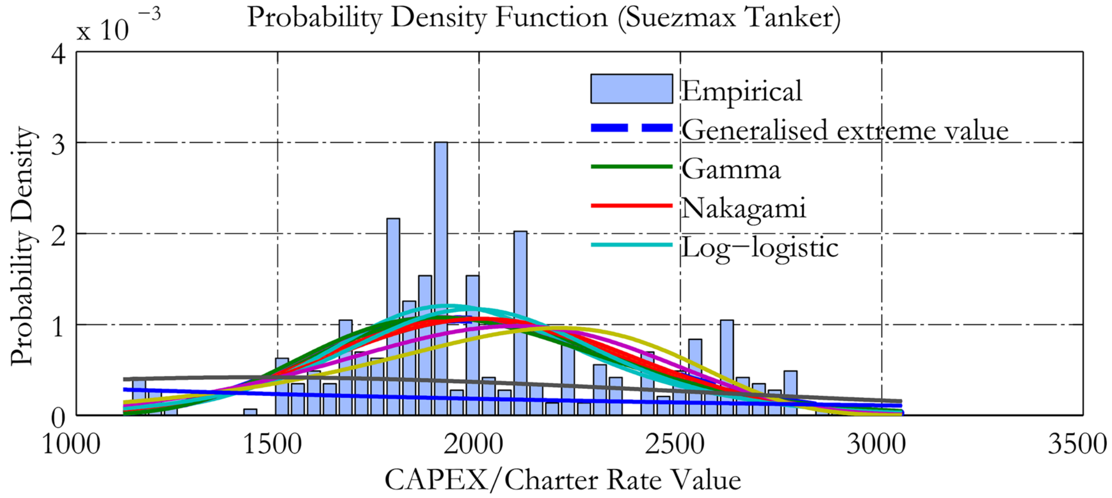


Figure 193: Suezmax tanker CAPEX/Time charter rate distributions

Table 58: Suezmax tanker CAPEX/Time charter rate distribution rankings

Distribution name	AICC	Parameter		
Generalised extreme value	5345.57	-0.22	357.00	1864.12
Gamma	5347.33	28.30	70.90	-
Nakagami	5347.54	7.31	4165952.64	-
Log-logistic	5349.09	7.58	0.11	-
Log-normal	5351.78	7.59	0.19	-
Rician	5351.98	1969.48	378.88	-
Normal	5352.24	2006.28	375.73	-
Birnbaum-Saunders	5352.36	1970.23	0.19	-
Inverse Gaussian	5352.48	2006.28	54346.73	-
t Location-Scale	5354.27	2006.27	375.23	4750958.12
Logistic	5359.30	1983.72	213.60	-
Weibull	5375.27	2163.57	5.69	-
Extreme value	5428.22	2199.23	382.23	-
Rayleigh	5799.11	1443.25	-	-
Exponential	6265.75	2006.28	-	-

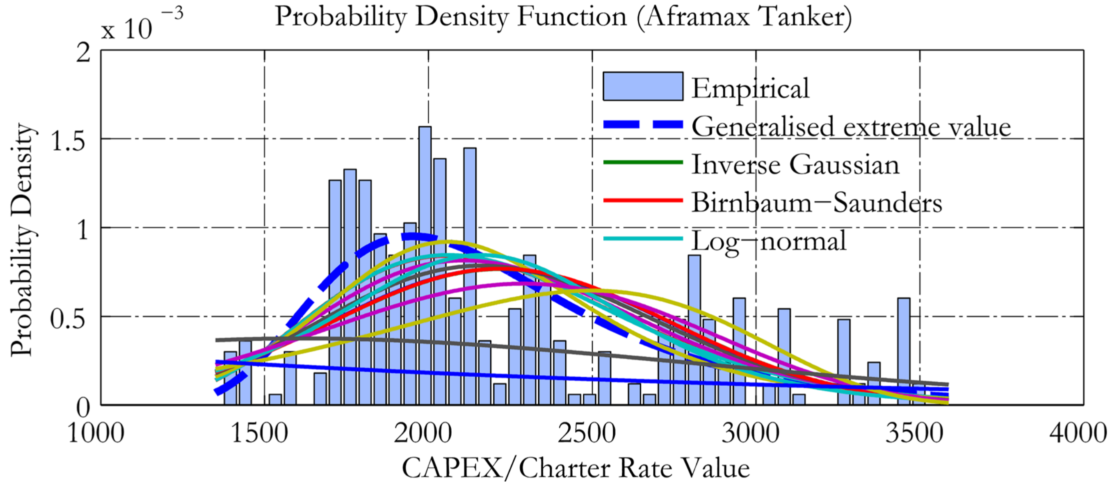


Figure 194: Aframax tanker CAPEX/Time charter rate distributions

Table 59: Aframax tanker CAPEX/Time charter rate distribution rankings

Distribution name	AICC	Parameter		
Generalised extreme value	5521.33	0.06	387.49	1972.60
Inverse Gaussian	5535.04	2220.73	43599.68	-
Birnbaum-Saunders	5535.29	2166.27	0.22	-
Log-normal	5536.15	7.68	0.22	-
Gamma	5549.24	19.70	112.72	-
Log-logistic	5551.96	7.66	0.13	-
Nakagami	5565.75	4.95	5201197.20	-
Rician	5587.15	2155.07	527.68	-
Normal	5588.69	2220.73	519.92	-
t Location-Scale	5590.72	2220.75	519.19	4232615.09
Logistic	5596.23	2160.04	295.57	-
Weibull	5615.51	2430.20	4.40	-
Extreme value	5706.11	2498.16	570.18	-
Rayleigh	5892.45	1612.64	-	-
Exponential	6339.68	2220.73	-	-

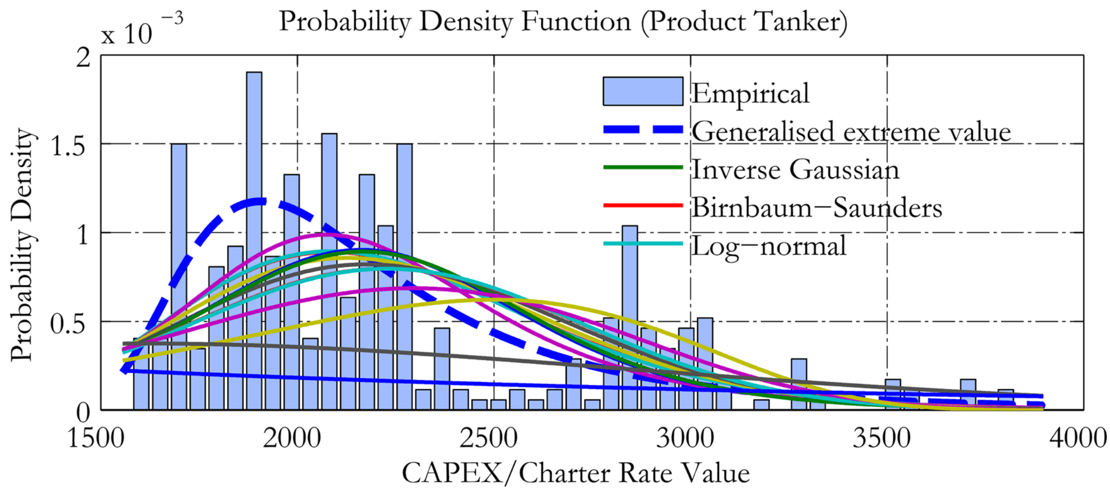


Figure 195: Product tanker CAPEX/Time charter rate distributions

Table 60: Product tanker CAPEX/Time charter rate distribution rankings

Distribution name	AICC	Parameter		
Generalised extreme value	5443.97	0.21	319.64	1968.17
Inverse Gaussian	5492.03	2227.92	49958.26	-
Birnbaum-Saunders	5492.39	2179.88	0.21	-
Log-normal	5492.85	7.69	0.21	-
Log-logistic	5504.13	7.67	0.12	-
Gamma	5511.76	22.06	100.98	-
Nakagami	5533.99	5.43	5213780.04	-
Logistic	5556.13	2161.38	277.06	-
t Location-Scale	5558.65	2167.88	431.94	7.37
Rician	5559.85	2167.62	507.53	-
Normal	5561.46	2227.92	500.83	-
Weibull	5601.52	2432.15	4.42	-
Extreme value	5713.39	2500.02	591.34	-
Rayleigh	5889.84	1614.59	-	-
Exponential	6342.04	2227.92	-	-

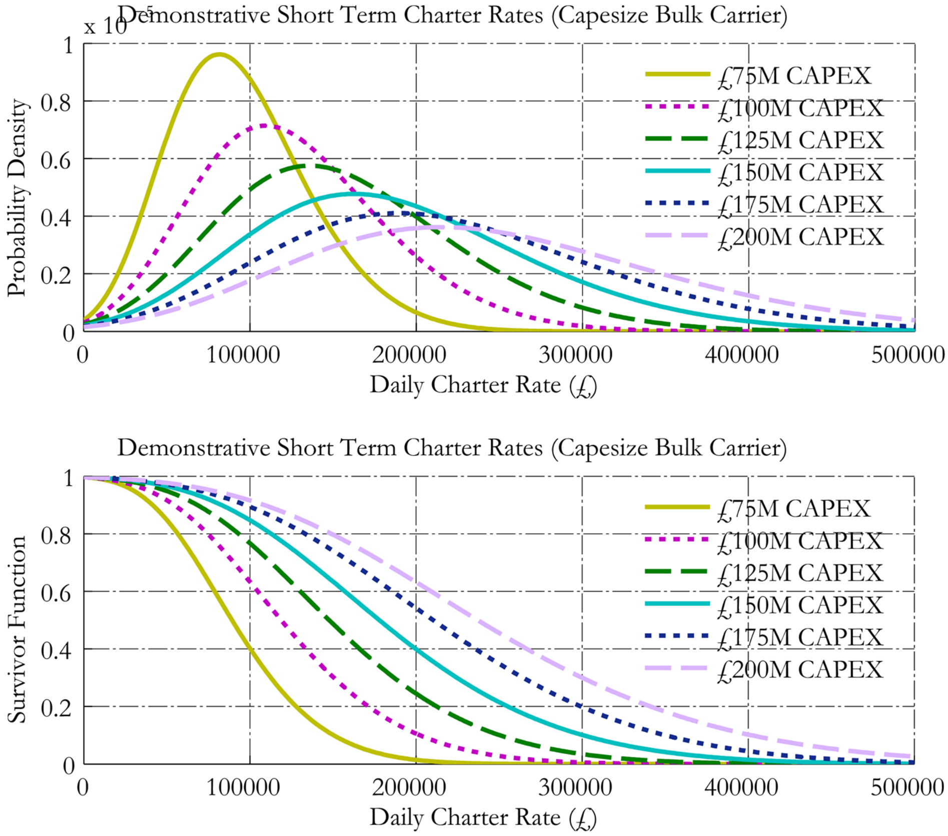


Figure 196: Demonstrative short term charter rates based on Capesize bulk carrier

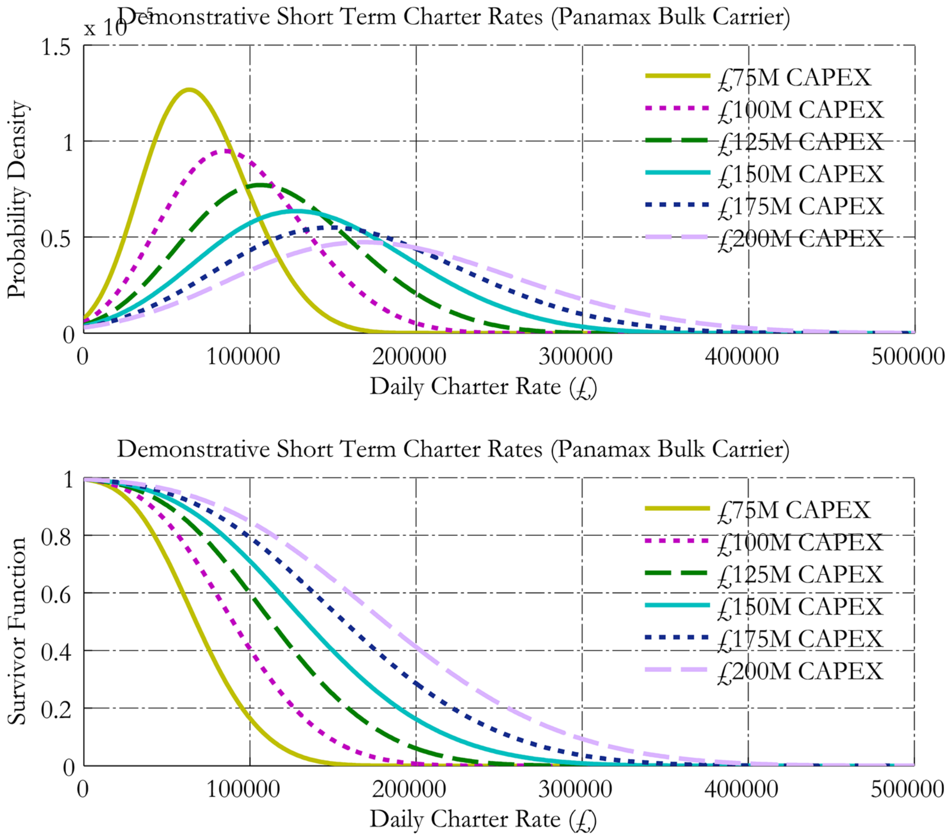


Figure 197: Demonstrative short term charter rates based on Panamax bulk carrier

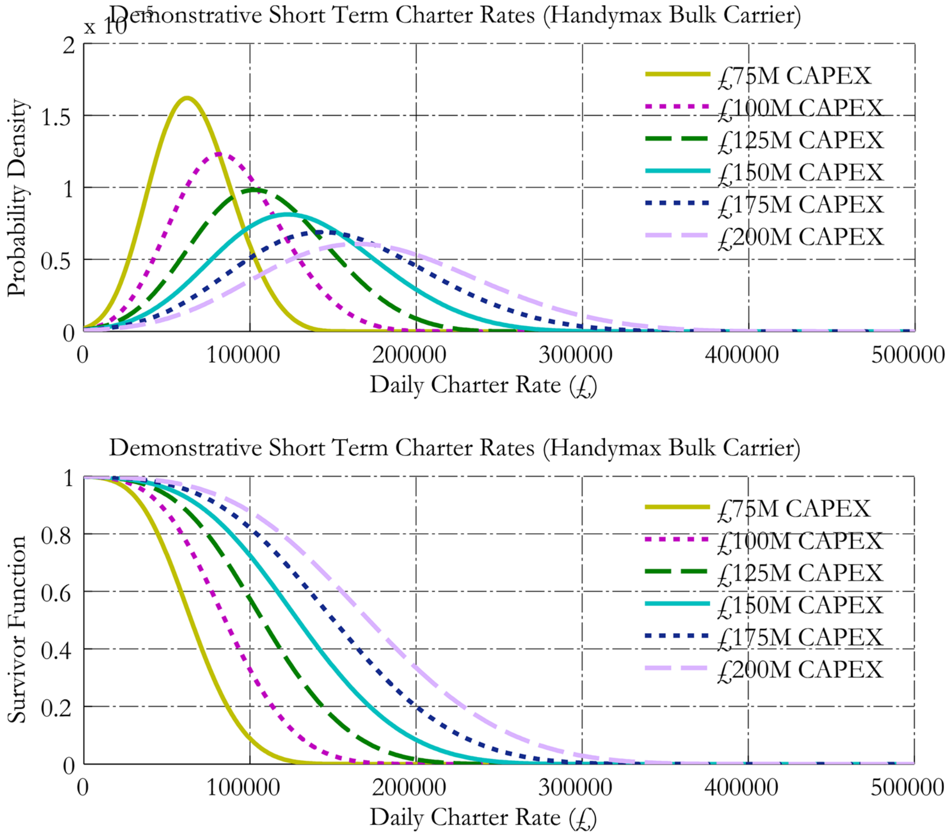


Figure 198: Demonstrative short term charter rates based on Handymax bulk carrier

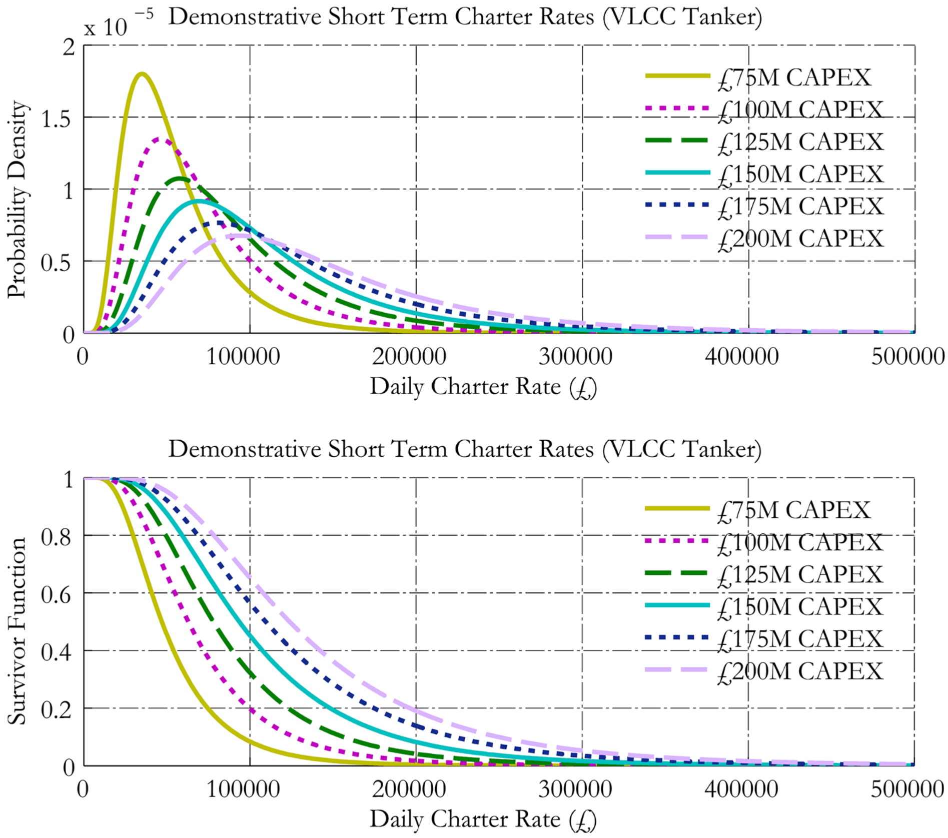


Figure 199: Demonstrative short term charter rates based on VLCC tanker

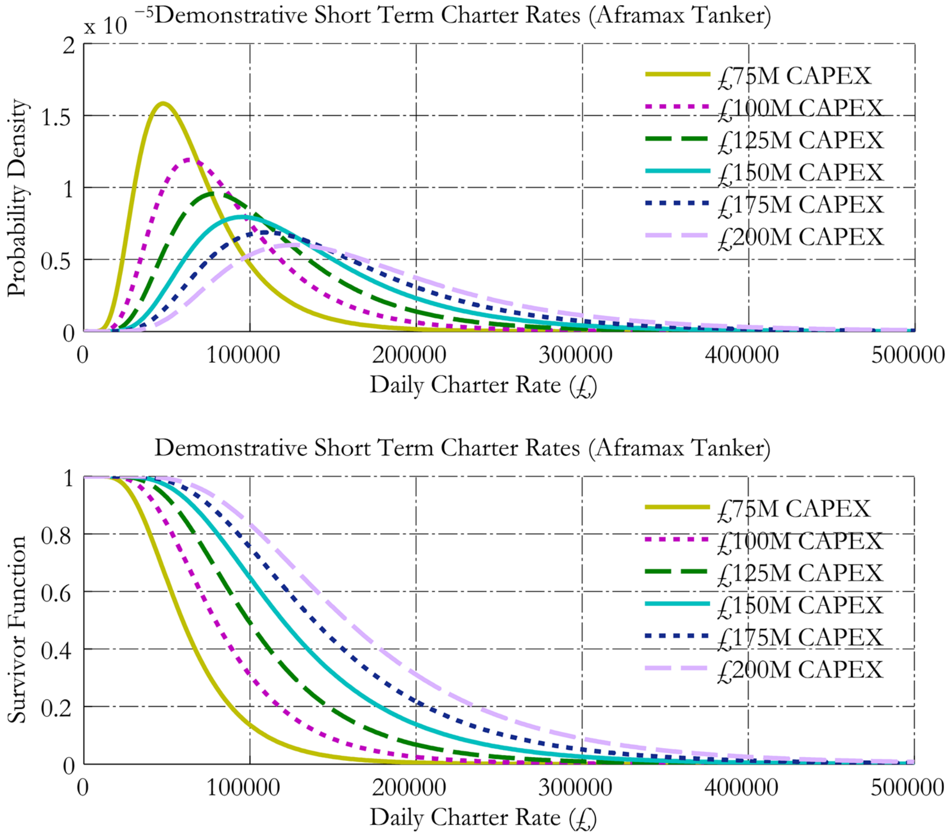


Figure 200: Demonstrative short term charter rates based on Aframax tanker

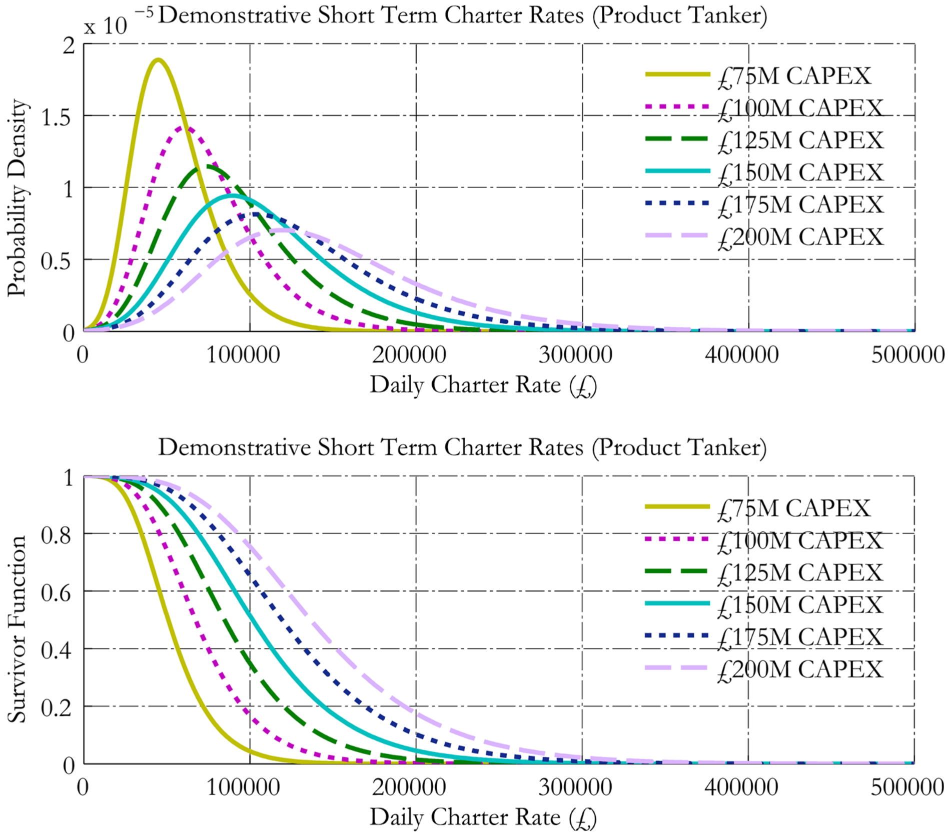


Figure 201: Demonstrative short term charter rates based on Product tanker

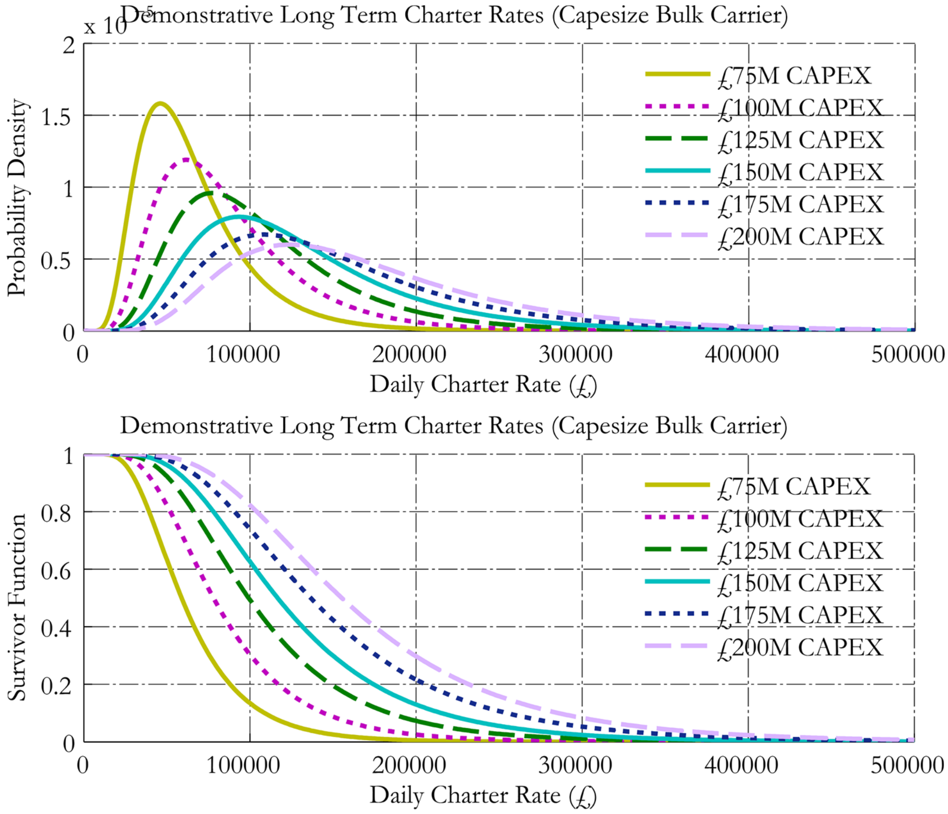


Figure 202: Demonstrative long term charter rates based on Capesize bulk carrier

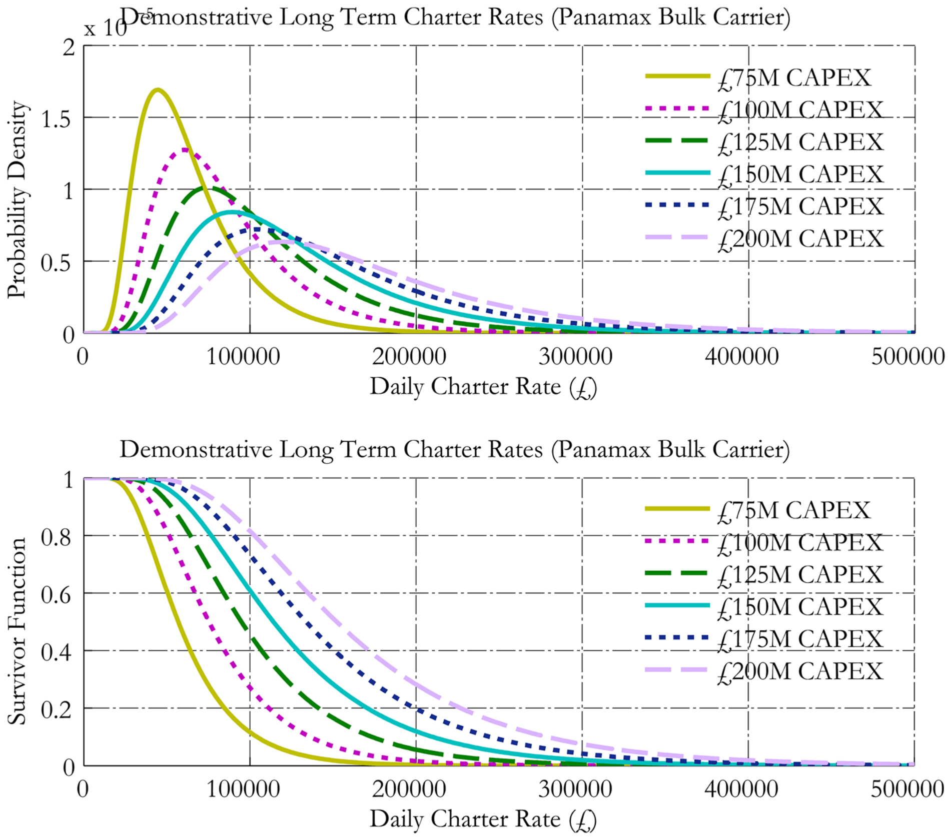


Figure 203: Demonstrative long term charter rates based on Panamax bulk carrier

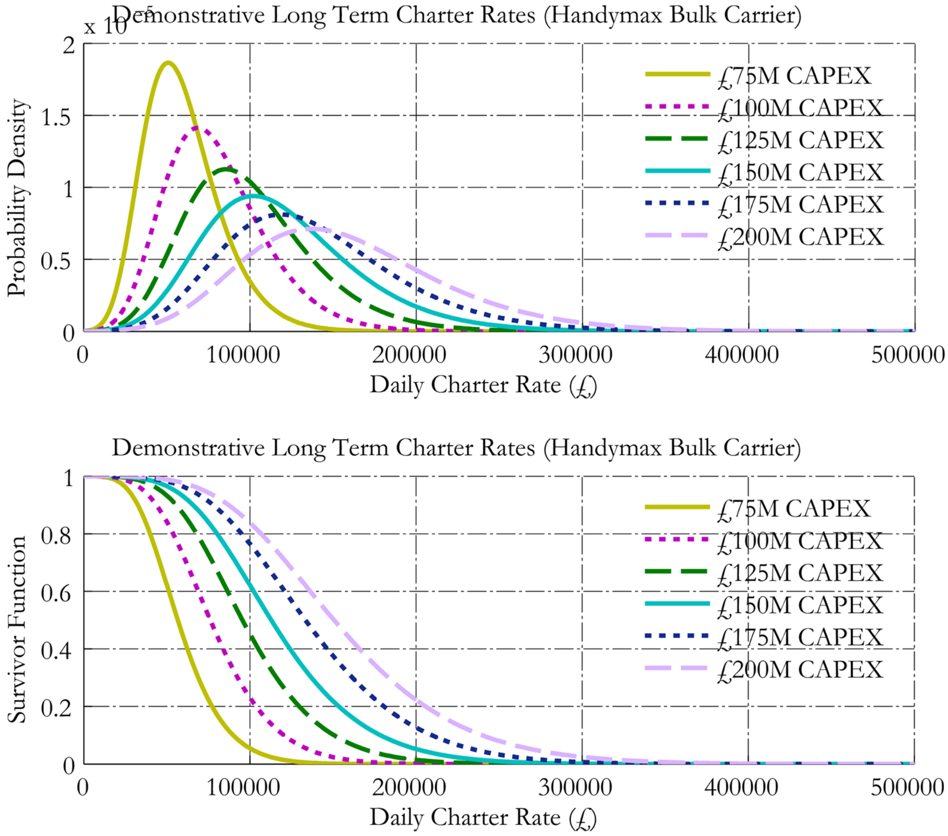


Figure 204: Demonstrative long term charter rates based on Handymax bulk carrier

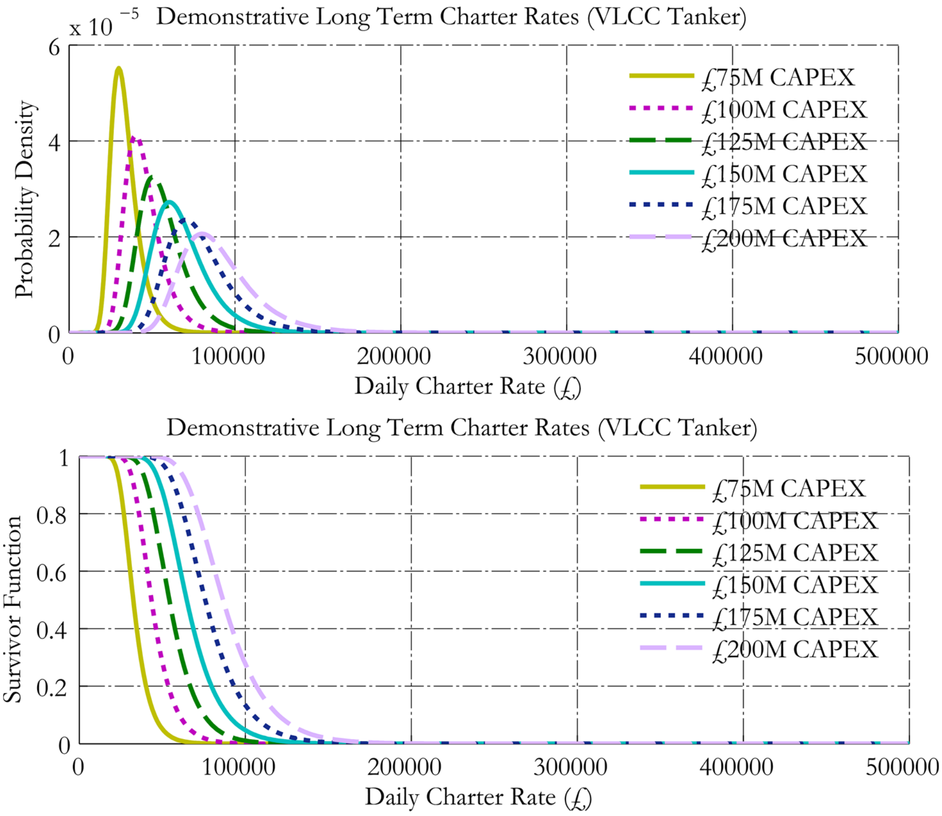


Figure 205: Demonstrative long term charter rates based on VLCC tanker

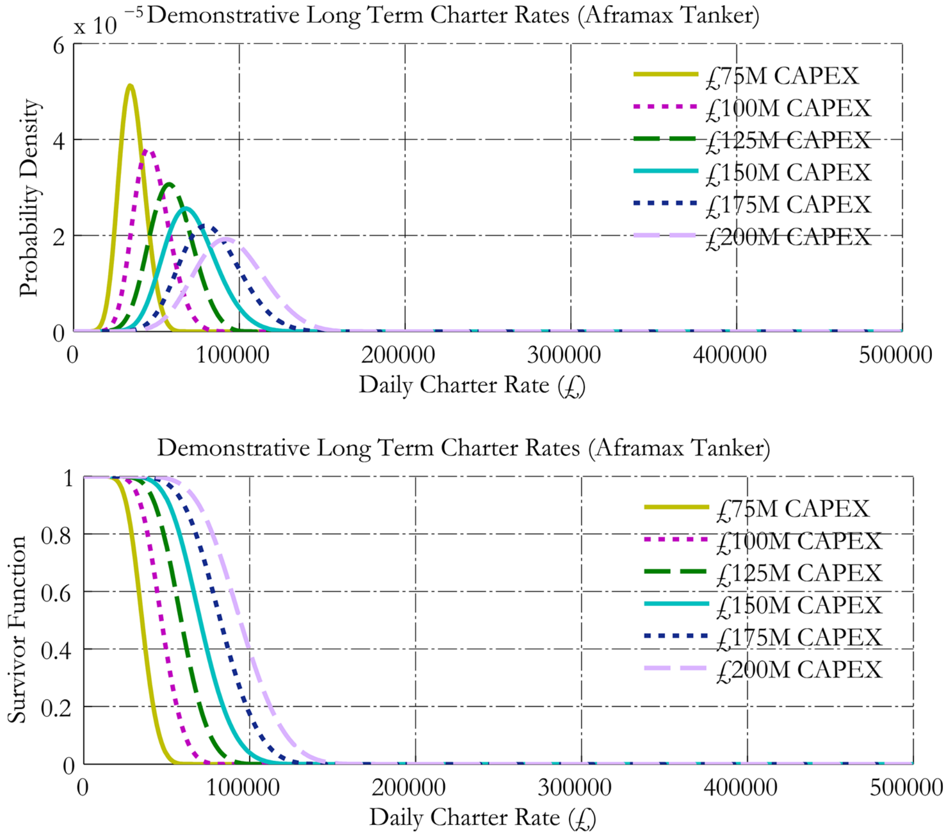


Figure 206: Demonstrative long term charter rates based on Aframax tanker

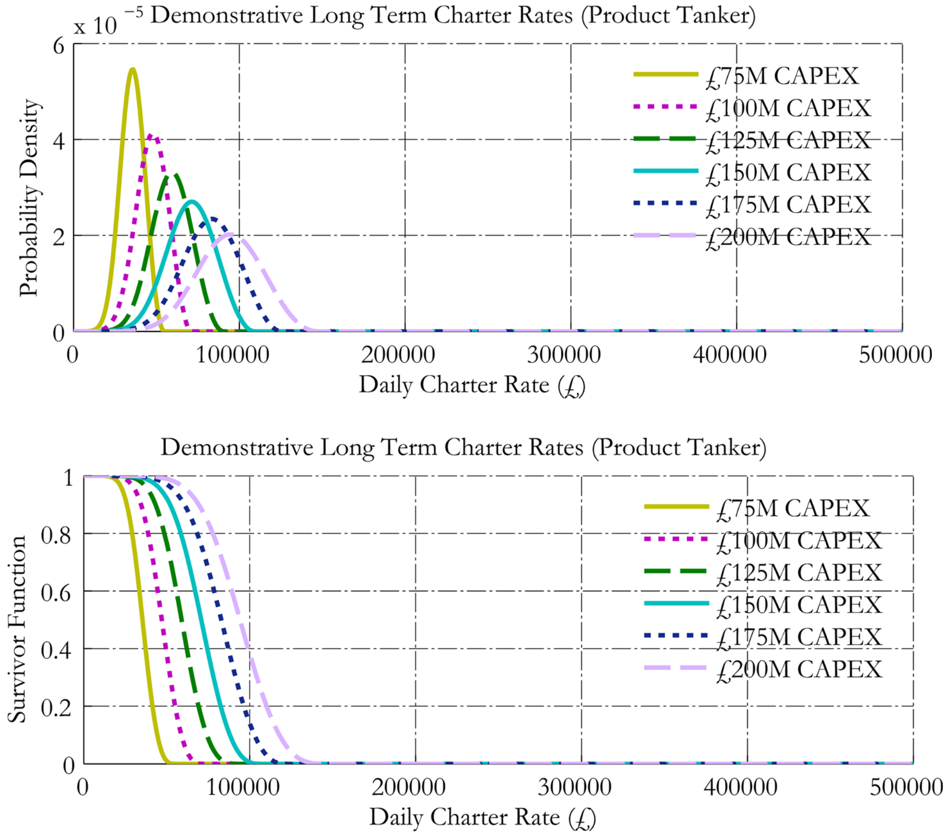


Figure 207: Demonstrative long term charter rates based on Product tanker

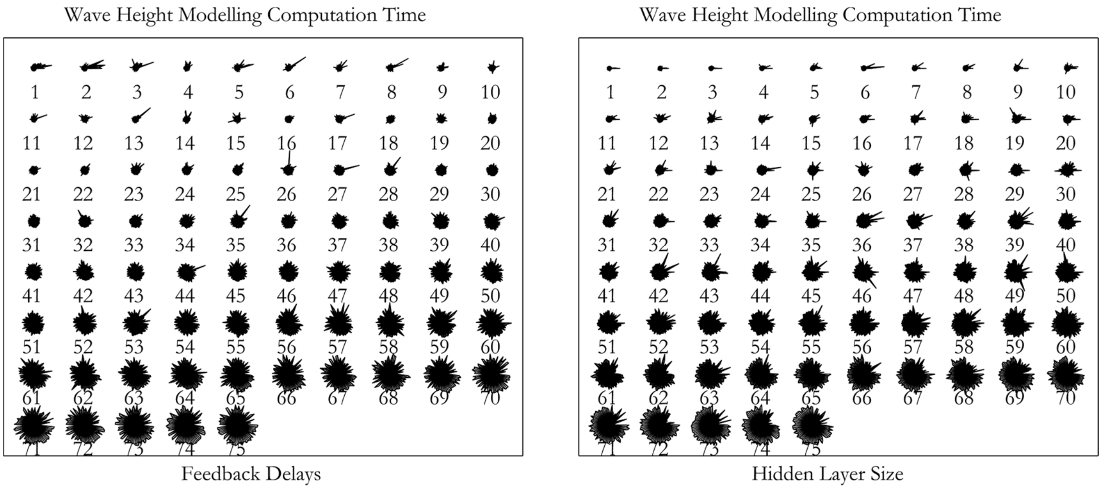


Figure 208: Wave height model computation time diagram

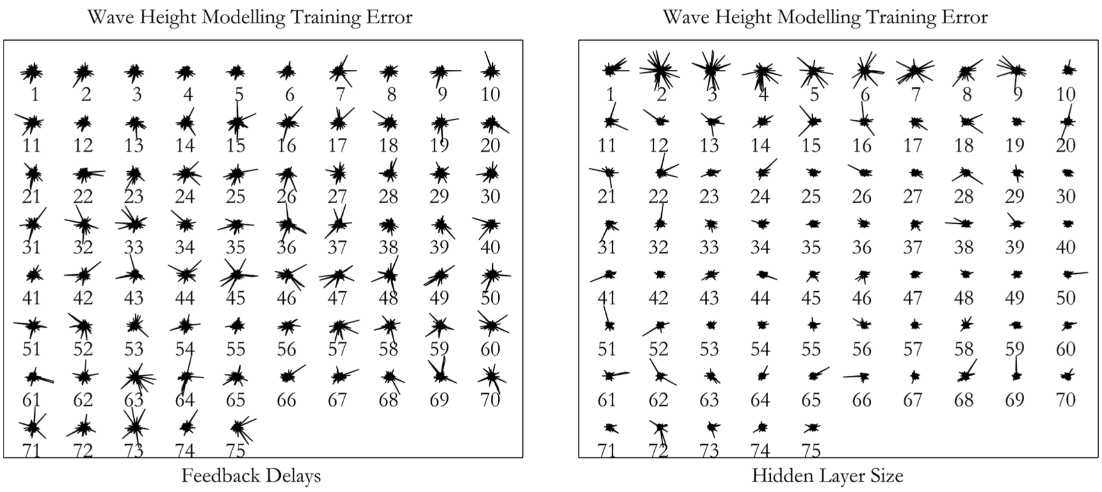


Figure 209: Wave height model training error diagram

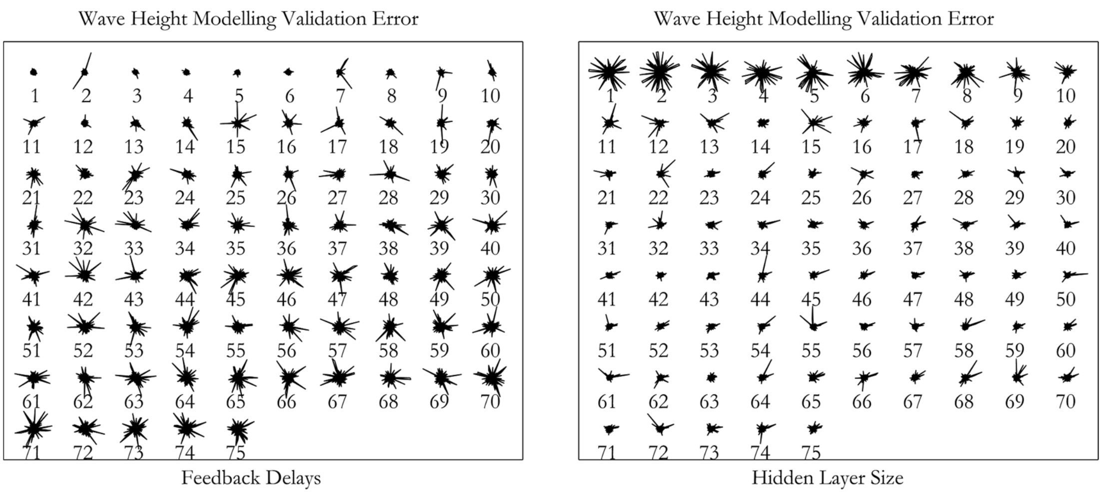


Figure 210: Wave height model validation error diagram

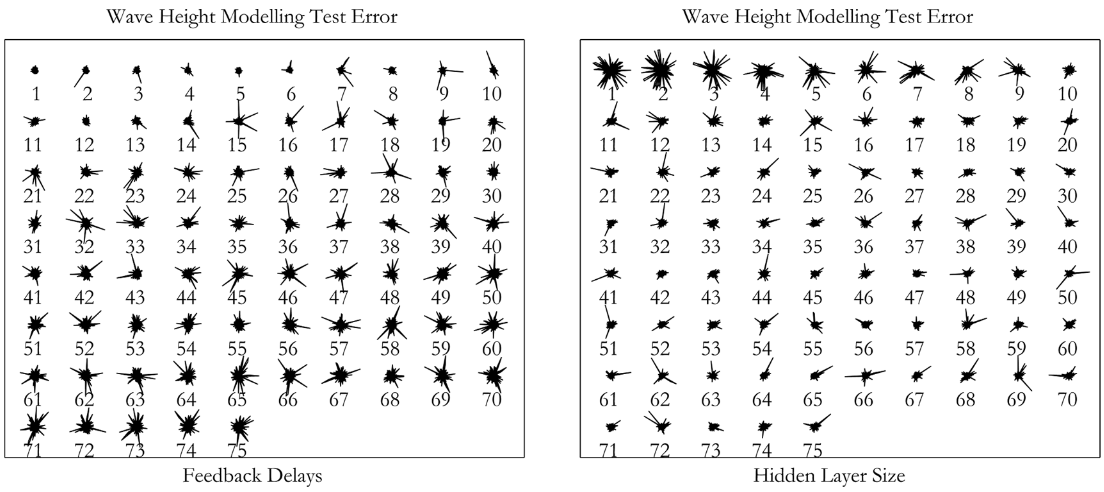


Figure 211: Wave height model test error diagram

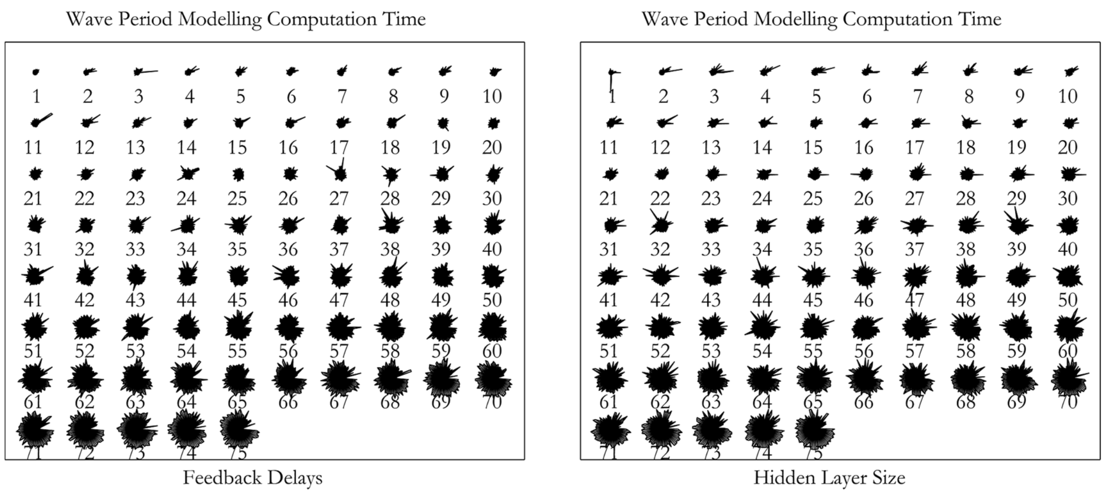


Figure 212: Wave period model computation time diagram

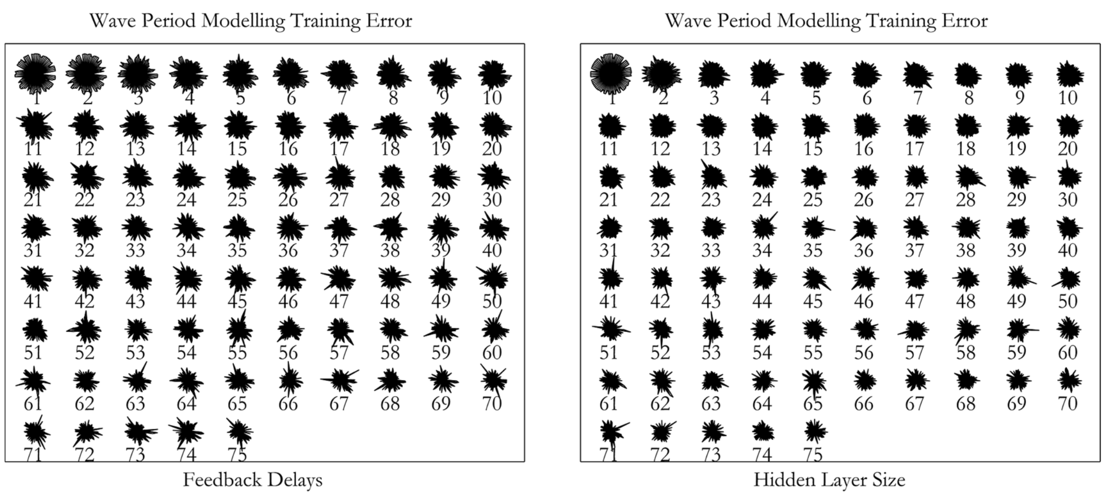


Figure 213: Wave period model training error diagram

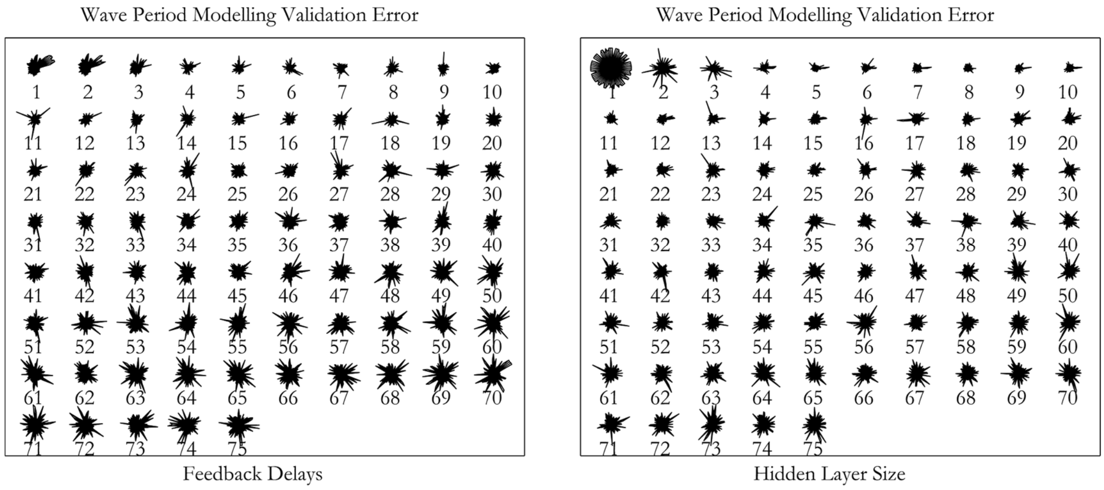


Figure 214: Wave period model validation error diagram

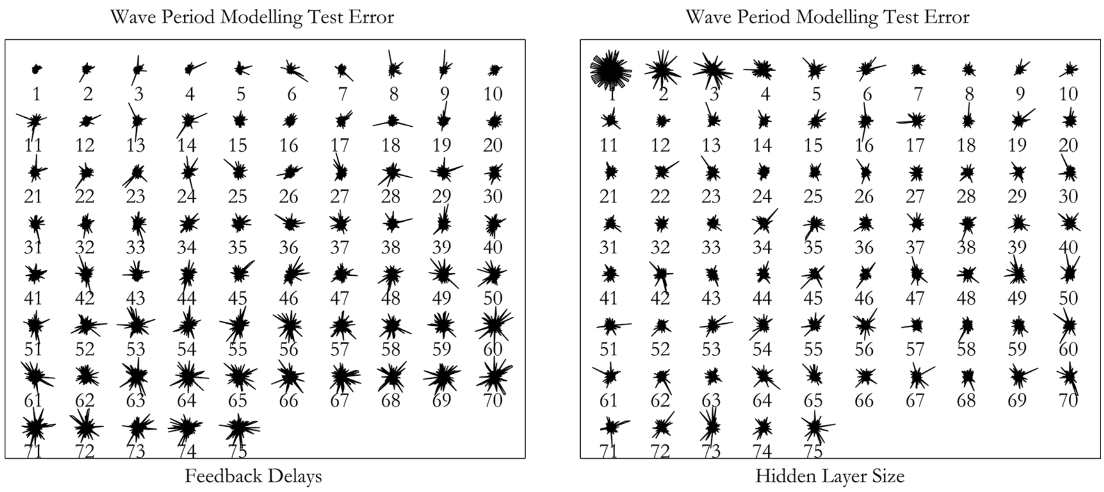


Figure 215: Wave period model test error diagram

Table 61: Neural network training – wind speed

Epoch	Time	Training Error	Validation Error	Test Error
0	0.908	278.4232	307.8506	348.1945
1	1.456	23.11677	22.54586	20.15825
2	1.894	2.826988	2.893081	3.235294
3	2.32	2.143496	2.408011	2.698578
4	2.74	1.677329	1.922774	2.195681
5	3.14	1.467223	1.623166	1.853133
6	3.573	1.215466	1.335807	1.535726
7	3.968	1.118286	1.198976	1.351637
8	4.4	1.045825	1.103475	1.223973
9	4.808	1.017895	1.073053	1.179652
10	5.207	1.001118	1.0565	1.155198
11	5.608	0.989914	1.045647	1.13914
12	6.026	0.982185	1.038072	1.127884
13	6.444	0.976728	1.032598	1.119766
14	6.894	0.972718	1.028464	1.11379
15	7.336	0.969624	1.025185	1.109305
16	7.743	0.967151	1.022507	1.105893
17	8.146	0.965152	1.020318	1.103289
18	8.569	0.963546	1.018562	1.101305
19	8.981	0.96227	1.017183	1.099791
20	9.399	0.961262	1.016113	1.098623
21	9.793	0.960461	1.015283	1.097705
22	10.197	0.959817	1.014633	1.096969
23	10.603	0.95929	1.014118	1.096367
24	11.013	0.958852	1.013704	1.095867
25	11.417	0.958481	1.013366	1.095448
26	11.846	0.958162	1.013088	1.095093
27	12.264	0.957885	1.012855	1.09479
28	12.699	0.957641	1.01266	1.094532
29	13.139	0.957424	1.012494	1.09431
30	13.565	0.957229	1.012351	1.09412
31	14.002	0.957052	1.012229	1.093956
32	14.384	0.95689	1.012123	1.093816
33	14.817	0.956741	1.01203	1.093695
34	15.201	0.956603	1.011948	1.093591
35	15.636	0.956475	1.011876	1.093502
36	16.092	0.956354	1.011813	1.093427
37	16.551	0.956282	1.011944	1.092569
38	16.967	0.954949	1.011392	1.093
39	17.361	0.954421	1.011322	1.093329
40	17.8	0.953841	1.012515	1.094242
41	18.218	0.952748	1.013456	1.096696
42	18.668	0.951488	1.013389	1.098691
43	19.097	0.950551	1.013451	1.099617
44	19.533	0.949936	1.013738	1.100254
45	19.96	0.94965	1.014091	1.100453

Table 62: Final neural network structure – wind speed

Input Weights			Layer Weight	Bias
0.413789	3.837121	0.30262	0.057701	1.803861
0.401553	-2.10077	0.135277	0.189995	0.179479
0.598745	-0.98649	0.116641	1.607419	-0.042
0.177053	-0.05406	-0.0184		
0.31025	-0.39018	0.042915		
-0.10235	-0.09211	0.008317		
0.481001	0.157682	-0.0344		
-0.28609	0.25325	-0.02791		
0.224233	-0.44082	0.060288		
-0.27908	0.616946	-0.07009		
-0.1005	0.044733	-0.00022		
0.218403	-0.21839	0.003945		
0.242201	-0.20169	0.028815		
-0.10297	0.116255	-0.0072		

Table 63: Neural network training – wave height

Epoch	Time	Training Error	Validation Error	Test Error
0	3.744	464.9087	463.169	471.589
1	7.718	0.349135	0.460406	0.405481
2	11.373	0.045815	0.093071	0.082912
3	15.53	0.017795	0.066854	0.057122
4	19.641	0.017692	0.0668	0.057139
5	23.492	0.017668	0.066891	0.057221
6	27.427	0.017647	0.066975	0.057277
7	31.438	0.017626	0.067052	0.05732
8	35.356	0.017607	0.067127	0.057356
9	39.352	0.017588	0.067199	0.057388
10	43.285	0.01757	0.067269	0.057417

Table 64: Final neural network structure – wave height input weights

0.121	0.596	-0.149	0.074	0.045	-0.148	-0.125	0.318	0.389	-0.215	0.232	-0.452	0.244	0.262	-0.125	0.038	-0.224	0.271	-0.244	-0.960	-0.265	0.539	-0.148	-0.387	0.163	-0.210	0.412	0.218	0.496	-0.253	0.211	-0.055	0.561	0.291	0.200	0.507	-0.164	0.151	-0.016	-0.296	-0.10
0.207	0.225	0.152	0.258	0.882	0.317	0.572	-0.303	-0.312	-0.134	0.164	0.084	0.263	0.026	-0.048	-0.340	0.013	-0.386	0.029	-0.187	-0.009	-0.236	-0.280	-0.084	-0.298	-0.058	-0.074	-0.248	-0.072	0.302	0.233	0.054	0.131	0.379	-0.304	0.744	0.129	-0.003	0.361	0.209	-0.04
0.274	0.113	-0.033	-0.112	0.068	0.142	0.154	-0.010	0.195	0.428	0.100	0.413	-0.108	-0.446	-0.271	-0.253	0.006	-0.467	0.313	0.318	-0.556	-0.494	-0.124	0.064	-0.357	-0.402	0.301	-0.123	0.291	-0.029	-0.202	-0.302	-0.419	-0.302	0.100	-0.475	0.240	0.039	0.439	-0.021	-0.25
-0.232	-0.487	0.083	-0.219	-0.008	0.075	0.291	-0.443	0.166	0.087	0.012	0.522	-0.124	-0.343	0.132	-0.053	-0.355	0.239	0.340	0.441	-0.698	-0.289	-0.114	-0.019	-0.342	-0.332	0.507	0.042	0.053	-0.194	-0.061	0.399	-0.007	-0.004	0.117	-0.762	0.131	0.211	-0.183	-0.230	0.140
0.346	0.003	0.260	-0.161	0.233	-0.098	-0.077	-0.283	0.248	0.131	0.249	0.409	-0.456	0.321	0.031	0.189	0.100	0.280	-0.331	0.163	-0.026	0.198	0.253	0.230	0.050	0.029	0.462	-0.376	0.141	-0.019	-0.474	0.179	-0.191	-0.256	0.021	-0.315	-0.192	-0.087	-0.070	-0.153	0.075
-0.299	-0.135	-0.380	-0.126	0.211	-0.265	0.164	0.288	0.266	0.314	-0.129	-0.265	-0.124	-0.190	0.323	0.275	0.050	-0.195	0.041	0.015	-0.109	-0.136	-0.243	0.472	0.139	0.441	-0.202	0.033	-0.379	0.291	0.133	0.307	0.659	0.345	-0.115	-0.534	-0.010	-0.136	-0.241	-0.153	-0.35
0.233	-0.066	-0.005	-0.290	0.132	-0.024	0.300	0.289	-0.075	0.034	-0.008	0.178	0.292	0.173	-0.293	0.326	-0.225	0.005	0.050	0.527	-0.211	0.052	0.002	-0.007	-0.358	-0.161	-0.124	-0.176	0.327	-0.239	0.001	-0.116	0.175	-0.254	-0.042	0.171	-0.249	-0.557	-0.236	-0.023	-0.15
-0.251	0.271	0.175	0.280	-0.175	0.249	-0.385	0.150	0.246	-0.244	0.369	0.276	0.287	-0.001	0.279	0.043	-0.123	-0.186	0.037	0.228	-0.009	-0.066	0.126	0.130	0.358	-0.321	0.265	0.151	-0.258	0.022	-0.169	0.099	0.045	-0.279	0.214	0.105	-0.140	-0.124	0.086	0.167	0.193
0.233	-0.013	-0.095	0.233	0.062	0.309	-0.084	0.214	0.085	0.397	-0.339	-0.032	-0.065	-0.366	0.359	0.375	-0.010	0.352	-0.342	-0.092	0.047	-0.042	0.144	-0.239	-0.168	0.021	-0.033	0.253	0.214	-0.225	-0.255	0.103	-0.224	0.395	0.248	0.185	0.391	0.267	0.141	0.466	0.036
0.395	0.247	-0.102	0.101	0.393	-0.149	0.034	0.558	-0.041	0.143	0.346	0.398	0.035	-0.327	-0.418	0.163	-0.051	0.447	0.143	-0.050	0.203	-0.229	0.255	0.025	-0.340	0.161	0.165	-0.360	0.247	-0.108	-0.212	-0.353	-0.137	-0.193	0.066	-0.144	-0.165	-0.091	0.368	-0.027	0.203
0.079	0.182	-0.341	0.407	0.190	-0.335	-0.048	-0.154	0.138	-0.247	0.062	-0.047	-0.010	-0.042	-0.417	-0.013	0.040	-0.300	-0.087	-0.129	0.267	0.261	-0.058	0.410	-0.305	-0.038	-0.021	0.377	-0.036	0.013	-0.246	-0.407	-0.107	0.022	-0.290	-0.008	-0.284	0.208	-0.114	0.361	-0.42
0.261	0.161	0.060	0.147	0.151	-0.365	0.267	-0.559	-0.132	-0.306	0.340	-0.388	0.046	0.100	0.130	0.378	-0.375	0.252	0.043	0.011	-0.090	0.067	0.211	0.518	0.038	-0.162	-0.348	0.111	0.019	0.152	-0.149	0.294	-0.166	0.369	-0.436	-0.226	0.160	0.318	0.263	-0.173	-0.30
0.281	0.195	-0.094	-0.208	-0.228	0.363	0.196	-0.053	0.052	-0.197	0.166	0.277	-0.065	-0.037	-0.039	-0.341	0.248	0.307	0.349	0.130	-0.185	0.172	-0.285	-0.244	-0.149	-0.235	0.081	-0.345	0.217	0.154	0.478	-0.125	-0.044	0.316	-0.082	-0.295	0.292	-0.391	-0.166	0.338	-0.12
-0.178	-0.237	0.239	-0.429	-0.257	0.080	-0.013	0.075	0.075	0.171	-0.364	-0.037	-0.437	0.306	-0.169	0.101	-0.111	0.076	0.371	-0.529	-0.342	-0.368	0.021	0.168	-0.257	0.356	0.054	-0.340	-0.438	-0.259	0.324	-0.434	-0.228	-0.194	-0.397	0.235	0.127	0.260	0.138	0.060	-0.15
0.132	-0.190	-0.361	-0.414	0.215	0.321	-0.301	-0.121	0.112	-0.187	0.222	0.092	-0.046	-0.224	0.215	0.208	0.201	-0.031	0.386	-0.141	0.091	0.312	-0.364	-0.130	0.360	-0.004	-0.203	0.084	-0.319	0.116	0.214	-0.053	0.050	0.236	-0.220	0.057	-0.376	0.028	0.313	0.350	-0.00
-0.209	0.140	0.317	-0.082	0.373	-0.410	-0.270	-0.214	-0.091	-0.057	-0.140	0.073	-0.356	-0.061	-0.206	-0.243	-0.465	0.038	-0.126	-0.502	-0.425	-0.173	-0.083	0.270	-0.351	0.323	-0.281	0.288	0.328	0.279	-0.321	-0.084	0.063	-0.230	0.017	0.048	-0.300	-0.107	0.450	-0.038	0.155
-0.100	-0.410	-0.104	0.258	-0.120	-0.299	0.036	-0.122	0.143	0.042	0.271	0.307	-0.201	-0.357	0.277	0.220	-0.422	0.189	0.115	0.251	0.034	0.222	-0.058	-0.178	-0.288	-0.094	-0.127	0.296	-0.058	0.200	-0.334	-0.357	0.497	-0.342	0.068	-0.110	-0.156	-0.074	0.442	-0.163	-0.05
-0.308	-0.213	-0.173	0.332	-0.229	-0.371	0.003	0.233	-0.300	0.363	-0.344	-0.048	-0.344	0.195	0.168	-0.287	0.037	-0.086	0.401	0.012	0.424	-0.123	-0.026	0.085	-0.139	-0.017	-0.047	-0.191	0.013	0.035	-0.147	-0.361	0.375	0.075	-0.152	-0.116	-0.333	0.072	-0.073	0.249	-0.36
0.319	0.065	-0.356	0.300	-0.427	-0.043	0.102	-0.426	-0.413	0.277	0.151	-0.177	-0.315	0.076	-0.313	0.419	-0.157	-0.270	0.418	0.316	0.013	-0.381	0.154	0.129	0.158	0.180	0.064	-0.051	0.483	0.205	0.115	-0.028	-0.119	0.188	-0.113	0.063	0.336	0.230	0.358	0.389	0.259
-0.427	-0.198	-0.411	-0.063	-0.242	-0.075	-0.070	0.119	0.274	-0.145	-0.108	0.304	-0.170	-0.322	0.003	0.079	-0.085	0.211	0.097	-0.071	0.086	0.326	-0.235	-0.058	-0.048	0.030	0.342	-0.010	-0.005	0.231	0.020	0.306	0.133	0.003	-0.073	-0.166	-0.462	-0.189	0.364	-0.211	0.302
0.199	0.252	0.221	-0.324	-0.099	0.336	0.147	0.371	-0.040	-0.417	0.150	-0.302	0.094	0.195	0.107	-0.105	-0.085	-0.184	-0.070	-0.397	0.341	0.259	-0.437	-0.096	0.284	-0.181	-0.383	0.264	-0.319	0.326	-0.527	-0.123	0.034	0.078	0.184	0.137	-0.036	-0.315	0.233	-0.190	0.117
0.312	-0.152	0.424	-0.354	0.271	0.512	-0.310	0.092	0.302	-0.132	0.232	0.073	0.271	0.281	-0.411	-0.082	-0.028	-0.120	0.433	0.019	-0.127	-0.143	0.031	0.268	-0.032	0.110	-0.308	0.315	-0.087	0.270	0.380	-0.075	-0.182	-0.221	0.071	0.065	-0.507	0.292	0.411	-0.173	0.103
-0.127	-0.137	0.249	0.208	-0.056	0.180	-0.012	-0.325	-0.381	-0.002	-0.127	-0.119	-0.114	-0.333	-0.084	-0.027	-0.311	0.201	-0.084	-0.090	-0.113	-0.320	0.143	-0.092	0.000	0.198	0.209	0.160	0.340	0.239	0.051	0.302	-0.319	-0.179	0.505	0.251	-0.039	0.277	-0.071	-0.062	-0.24
-0.104	-0.424	-0.041	-0.100	0.356	-0.062	0.236	-0.030	-0.029	0.309	0.423	0.088	0.436	0.163	0.067	0.457	0.480	0.342	0.123	0.028	-0.064	0.284	-0.394	-0.044	-0.012	0.025	-0.446	0.137	0.303	-0.260	-0.220	-0.216	0.286	0.082	-0.111	-0.429	-0.008	0.314	0.327	0.327	-0.26
0.027	0.202	-0.324	0.482	0.239	-0.171	-0.384	0.007	0.238	0.001	-0.113	-0.040	-0.304	-0.331	0.341	0.247	-0.104	0.162	-0.348	0.016	0.049	-0.208	0.165	0.036	0.313	-0.085	-0.374	-0.174	-0.041	0.235	-0.175	-0.259	0.213	-0.005	0.432	0.380	0.179	0.090	0.224	0.291	-0.38
-0.146	-0.451	0.257	0.064	-0.182	-0.229	-0.010	-0.190	-0.320	-0.342	-0.375	-0.169	-0.277	-0.065	0.367	-0.159	-0.240	0.027	0.290	0.055	-0.503	-0.289	-0.243	0.229	-0.017	-0.030	0.140	0.070	0.111	0.295	0.099	0.355	0.040	-0.276	-0.332	-0.036	-0.255	0.250	0.150	0.078	0.168
0.008	0.002	-0.040	0.407	-0.198	-0.185	-0.194	0.167	0.275	0.434	-0.259	0.203	0.121	-0.106	0.026	-0.070	0.093	0.214	-0.224	-0.341	0.237	-0.073	0.396	-0.356	-0.310	0.286	0.323	0.420	0.254	-0.351	-0.013	0.444	-0.005	0.293	-0.349	0.306	0.420	-0.002	-0.053	-0.089	0.183
-0.411	-0.062	0.232	0.070	0.124	0.168	-0.157	0.353	0.381	0.015	0.436	-0.109	-0.061	-0.269	-0.252	0.154	0.275	0.047	0.175	-0.036	0.037	-0.281	-0.006	-0.265	-0.388	0.172	0.103	-0.230	-0.194	0.150	0.122	-0.295	-0.198	-0.406	-0.052	-0.024	-0.334	0.075	-0.430	-0.214	0.387
0.431	-0.224	-0.078	0.299	-0.128	0.247	0.227	0.126	-0.348	-0.095	0.324	0.137	-0.123	0.091	-0.208	-0.024	0.483	0.294	-0.250	0.148	-0.288	0.381	-0.355	-0.167	0.202	-0.254	0.017	0.255	0.150	-0.193	-0.047	-0.122	0.084	0.055	-0.234	0.228	0.079	-0.441	0.074	0.431	0.244
0.157	0.112	-0.205	0.084	-0.265	-0.026	0.263	0.293	0.245	0.395	-0.291	0.031	0.078	0.340	0.166	-0.118	0.240	0.153	0.070	-0.312	0.294	-0.298	0.016	-0.359	-0.111	0.458	-0.280	0.322	0.072	-0.059	-0.280	-0.182	0.248	-0.362	0.200	-0.102	0.162	0.299	-0.106	-0.131	0.320
0.264	0.291	-0.300	0.080	-0.195	0.176	-0.056	-0.150	0.186	0.039	0.204	-0.324	0.118	-0.430	0.297	0.182	0.363	-0.417	0.331	-0.098	-0.015	-0.086	-0.229	0.070	-0.270	-0.057	0.106	0.422	-0.012	0.378	-0.166	-0.158	0.176	-0.335	0.243	0.023	0.196	-0.024	-0.165	0.403	0.168
-0.075	0.019	0.132	0.026	-0.295	-0.036	0.447	-0.035	-0.344	-0.386	-0.342	0.271	-0.089	0.037	0.016	-0.480	0.251	-0.215	-0.210	0.068	-0.085	-0.005	0.166	0.007	0.077	-0.117	-0.200	-0.039	-0.394	0.303	0.290	-0.279	0.114	-0.333	0.403	-0.027	-0.010	0.209	0.166	-0.027	-0.37
-0.054	-0.100	0.199	-0.475	0.282	0.154	0.381	0.028	-0.163	-0.209	0.174	0.420	-0.178	0.224	-0.337	0.108	-0.198	0.149	-0.195	-0.542	-0.095	0.207	-0.218	-0.164	0.120	0.433	-0.196	-0.069	0.142	0.194	-0.166	0.214	-0.277	-0.150	-0.386	-0.119	-0.101	-0.194	-0.191	-0.052	0.370
0.298	-0.131	0.036	0.020	-0.071	-0.141	0.353	-0.238	0.286	-0.420	-0.141	0.195	0.063	-0.278	0.428	-0.139	-0.043	0.027	0.308	0.279	0.101	-0.001	-0.111	-0.361	0.157	-0.211	-0.185	-0.081	0.248	-0.298	0.399	-0.146	-0.452	-0.003	0.288	-0.339	-0.379	0.275	0.084	0.059	0.405
0.332	-0.315	-0.379	0.051	0.231	-0.305	-0.370	0.020	0.087	0.031	-0.424	0.146	0.390	0.336	-0.321	-0.163	-0.280	-0.001	0.083	-0.305	0.278	0.261	0.169	-0.095	-0.359	0.255	0.404	-0.272	-0.434	0.342	0.005	0.244	-0.037	-0.216	-0.189	-0.366	0.068	0.097	0.009	-0.277	0.413
-0.014	0.021	-0.254	0.040	0.103	0.276	-0.196	-0.136	-0.253	0.350	-0.182	-0.145	-0.456	0.248	0.035	0.244	0.316	0.113	0.143	-0.230	-0.034	0.480	0.065	0.106	0.365	0.327	-0.239	-0.369	-0.059	-0.354	0.047	0.383	-0.355	-0.064	-0.005	0.180	0.195	0.070	-0.116	0.413	0.202
0.206	0.120	-0.046	0.147	-0.147	0.236	-0.016	0.127	0.358	0.029	-0.055	-0.220	-0.060	-0.332	-0.078	0.027	-0.115	0.207	0.027	0.014	0.238	-0.311	0.050	-0.024	-0.127	-0.096	0.346	-0.247	0.030	0.300	-0.320	-0.179	-0.219	0.324	0.006	-0.231	0.052	0.057	-0.084	-0.345	0.169
0.005	-0.139	-0.366	-0.233	-0.178	-0.296	0.375	-0.223	-0.330	-0.094	0.244	-0.292	0.417	-0.140	-0.116	-0.166	0.175	-0.426	0.337	-0.286	-0.215	0.216	-0.278	-0.002	0.126	0.275	0.260	0.218	-0.026	-0.212	0.087	-0.206	0.307	0.148	0.281	0.125	-0.061	-0.127	0.173	0.460	0.225
0.294	-0.004	0.170	0.185	0.091	0.242	-0.240	0.299	-0.310	0.058	-0.047	-0.336	0.306	0.096	0.284	0.151	0.338	0.037	0.349	0.337	-0.005	0.272	-0.070	0.342	-0.212	0.087	-0.128	-0.343	0.248	0.239	0.418	-0.160	0.305	0.038	-0.024	0.174	0.405	-0.285	0.197	-0.212	-0.07

Table 65: Final neural network structure – wave height

Layer Weight	Bias
-0.09416	-1.51898
0.343097	-1.39223
0.51055	1.490832
0.580223	-1.36939
0.228219	1.283681
0.40748	1.208253
0.113006	1.046872
0.313174	-1.07452
0.040209	-0.90002
0.017228	0.805229
-0.11428	-0.68667
-0.13763	0.75443
-0.13902	-0.47916
0.083066	-0.52724
-0.00348	0.449913
0.415912	-0.86227
-0.169	0.230354
-0.23673	-0.1856
0.0662	0.067916
-0.42419	-0.02707
-0.27147	0.000863
0.222406	-0.13407
0.285074	-0.17046
-0.23957	-0.19131
0.243491	0.303998
-0.36806	-0.37854
0.192934	0.356746
-0.00901	0.522125
0.22248	0.49792
0.000333	-0.722
0.137764	-0.69239
-0.23909	0.912612
0.324868	0.769244
-0.09971	0.972656
-0.25598	1.2303
-0.66856	1.214691
-0.11343	-1.1811
0.352289	1.032408
0.083861	-1.38626
-0.36997	-1.41267
0.022218	-1.52287

Table 66: Neural network training – wave period

Epoch	Time	Training Error	Validation Error	Test Error
0	0.397	14.18248	15.10031	13.82094
1	0.796	2.385355	2.363644	2.902288
2	1.206	2.308448	2.640227	2.367222
3	1.627	0.732183	0.887382	1.08241
4	2.045	0.604223	0.727828	0.760663
5	2.456	0.559556	0.671903	0.696554
6	2.855	0.499336	0.606019	0.616455
7	3.32	0.444688	0.555982	0.559283
8	3.7	0.356543	0.468238	0.448863
9	4.084	0.152806	0.213373	0.182938
10	4.477	0.132567	0.197864	0.160814
11	4.853	0.066874	0.113637	0.092262
12	5.259	0.063049	0.110598	0.087668
13	5.652	0.060283	0.107585	0.084378
14	6.06	0.059847	0.107079	0.08348
15	6.454	0.059679	0.106816	0.082982
16	6.844	0.059584	0.106634	0.082663
17	7.253	0.059522	0.106502	0.082443
18	7.636	0.059478	0.106404	0.082283
19	8.016	0.059446	0.106329	0.082162
20	8.42	0.059421	0.106271	0.082068
21	8.85	0.059401	0.106224	0.081991
22	9.224	0.059385	0.106185	0.081929
23	9.628	0.059372	0.106153	0.081877
24	10.013	0.059361	0.106126	0.081832
25	10.425	0.059352	0.106102	0.081794
26	10.805	0.059344	0.106082	0.081761
27	11.215	0.059337	0.106064	0.081731
28	11.614	0.059331	0.106048	0.081706
29	12.036	0.059326	0.106034	0.081682
30	12.407	0.059323	0.105828	0.081586
31	12.804	0.059287	0.105852	0.081482
32	13.187	0.059276	0.105849	0.081434
33	13.593	0.059271	0.105844	0.081404
34	13.965	0.059267	0.105838	0.081382
35	14.351	0.059265	0.105833	0.081366
36	14.731	0.059263	0.105828	0.081354

Table 67: Final neural network structure – wave period

Input Weights	Layer Weight	Bias
-0.53993	-1.550096249	-0.191027643
-0.12285		
0.035465		
0.000274		
0.020599		
0.013023		
-0.00332		
-0.0073		
-0.02899		
-0.00503		
-0.01334		
-0.00181		
0.002777		
0.012393		
0.001903		
0.026366		
0.003099		
-0.00712		
-0.00636		
-0.00703		
-0.00086		
-0.00825		
0.011446		
-0.05009		
0.024728		
0.001168		
0.015473		
-0.00289		
0.012361		
0.002985		
0.004581		
0.000257		
-0.00936		
0.00796		
-0.00943		
-0.01637		
-0.00198		
0.006001		
-0.00884		
0.019956		
-0.01321		
0.004379		
0.010364		
-0.00252		
0.004213		
-0.00323		
-0.01505		

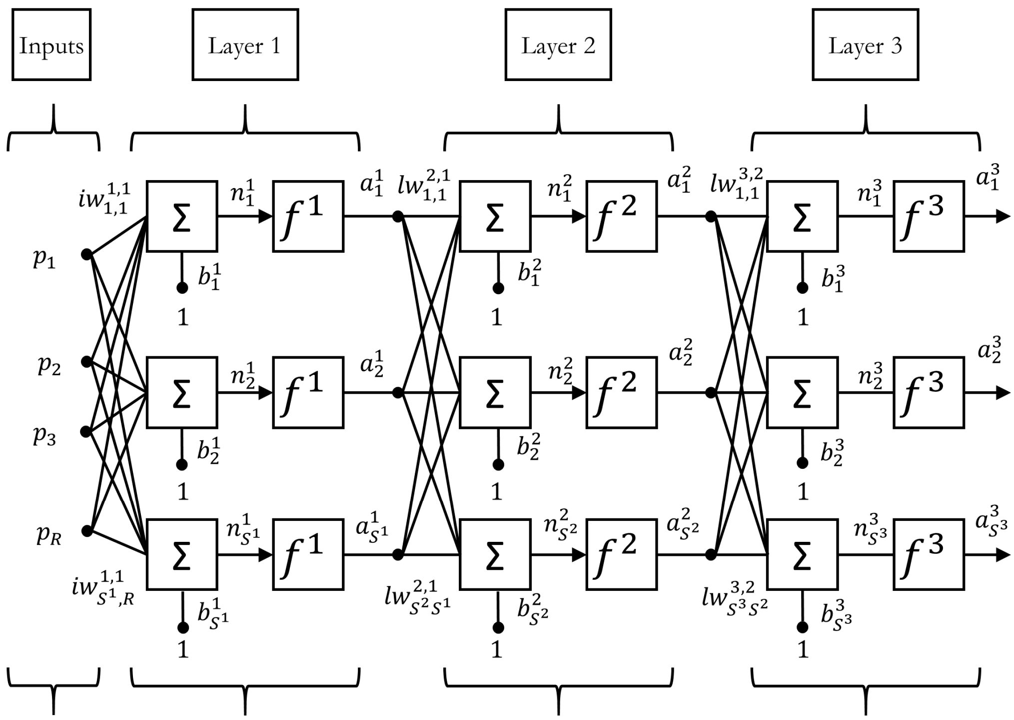
Input Weights	Layer Weight	Bias
0.001698		
0.004828		

11 Appendix B

Data modelling

- Artificial neural networks

Artificial neural network is a collection of interrelated neurons, which incrementally learn from data to capture essential linear and nonlinear trends in complex datasets; so that it provides reliable predictions/estimations for new situations, which may contain noise and partial information. Neurons, which are the local data processing units in a network, form parallel networks. The function of parallel networks is determined by the network structure (i.e., the organisation of neurons and the relation of each neuron with other neurons), the connection strengths between neurons, and the processing performed at neurons. Artificial neural networks are capable of time-series modelling through capturing temporal patterns in the data as a form of past memory that is embedded in the model, and defining future behaviour by implementing the learnings from the past memory (Samarasinghe, 2007). A typical structure of multi-layer feedforward neural network system is illustrated in Figure 216.



$$a^1 = f^1(IW^{1,1}p + b^1) \qquad a^2 = f^2(LW^{2,1}a^1 + b^2) \qquad a^3 = f^3(LW^{3,2}a^2 + b^3)$$

$$a^3 = f^3(\mathrm{L}W^{3,2}f^2(LW^{2,1}f^1(\mathrm{I}W^{1,1}p+b^1)+b^2)+b^3)$$

Figure 216: Typical structure of multi-layer feedforward neural network system
Adapted from Hagan *et al.* (1996)

For each layer, W, b, and a denote the weight matrix, bias vector, the output vector, respectively. The number of the layers is appended as a superscript to the variable of interest. R and S present the number of elements in the input vector and the number of neurons in the layers, respectively. IW and LW denote layer weight and input weight matrices. In the neural networks, each p value (climate observation) is connected to each neuron through the weight matrix W. The summers in the neurons transform the weighted input value and bias to the scalar output form n; after that, the neurons use differentiable transfer function f to generate the output. The outputs of each intermediate layers provide input for the following layer. The final layer, which produce the final network output, is also called output layer.

Defining the number of hidden layers, neurons, and the number of lags for the network

At the first stage, the number of hidden layers has to be defined. In principle, increasing the number of hidden layers in the network structure increases the complexity of the training process. Hammer (2014) stated that feedforward neural networks are universal approximators, which are capable of representing any reasonable function at any desired precision with at least one hidden layer and sufficient number of neurons. In many practical problems, one hidden layer in the network structure is sufficient for modelling any kind of multivariate function (Chui and Li, 1992, Li, 1996, Ismailov, 2014). Therefore, the number of hidden layers is set to '1'. At the second stage, the number of neurons in the hidden layers has to be defined.

In this case, increasing the number of neurons leads the network to decrease the error; however after reaching the optimum number of neurons, the error has a tendency to increase again due to over-fitting. Furthermore, the high number of neurons in hidden layers require more computation time. Due to the fact that there is no standard approach to determine the exact number of hidden neurons (Kermanshahi *et al.*, 1993); it is generally determined by testing the neural networks with different number of neurons, and comparing the errors (Yuan *et al.*, 2003, Dixit and Dixit, 2008). Therefore, the number of neurons in hidden layers can be defined by testing different scenarios.

At the final stage, the number of lags, which is important to preserve the autocorrelation, has to be defined. The number of lags can be defined from the autocorrelation coefficients. The autocorrelation function, which examines how a time series value is correlated with itself at different lag orders, is a useful function to assess the influence of previous time steps on the current time step. In this context, an autocorrelation structure is exported into the network structure, so that the feedforward neural network has a short-term memory capability. However, autocorrelation may remain significant until a high lag order; therefore, partial autocorrelation coefficients can be employed in practical applications (Evans, 2002, Dietz, 2010). The partial autocorrelation is a measure of relationship after removing the effects of the other time lags. The calculation of autocorrelation and partial autocorrelation coefficients are performed by the equations below,

$$ACF_i = \frac{\widehat{cov}(x_t, x_{t-i})}{\widehat{var}(x_t)} \quad \text{Equation 79}$$

$$cov(x_t, x_{t-i}) = \frac{1}{n-1}\sum_{t-i+1}^{n}(x_t - \bar{x})(x_{t-i} - \bar{x}) \quad \text{Equation 80}$$

$$\widehat{var}(x_t) = \frac{1}{n-1}\sum_{t-1}^{n}(x_t - \bar{x})^2 \quad \text{Equation 81}$$

$$PACF_i = \frac{ACF_i - \sum_{j=1}^{i-1} PACF_{i-1,j}\, ACF_{i-j}}{1 - \sum_{j=1}^{i-1} PACF_{i-1,j}\, ACF_{i-j}} \quad \text{Equation 82}$$

where $\bar{x}$ is the mean of x_t. It should be noted that the PACF in the first lag is equal to the ACF in the first lag. The values in the ACF and PACF fit into a range between [-1, 1]; the values become closer to -1 or 1 represent a strong relation between the current value and the particular lag order.

Data pre-processing and post-processing

In order to perform the neural network training more efficiently, certain pre-processing and post-processing steps are performed (Figure 217). Sigmoid transfer functions in Figure 218 are generally used in the multilayer neural networks (Eberhart and Dobbins, 1990); however, if the input of the sigmoid transfer function becomes greater than 3, these functions become saturated. This is because, the gradient of sigmoid transfer functions becomes relatively small in this particular case and therefore, training of the neural network systems continues significantly for longer periods. In this context, the inputs of the neural network system are normalised as recommended by Das (2013); so the network inputs fall into a normalised range [-1, 1]. The normalised input values are calculated by Equation 83 below;

$$x_n = (x_{n-max} - x_{n-min})(x_o - x_{o-min})/(x_{o-max} - x_{o-min}) + x_{n-min} \quad \text{Equation 83}$$

where x_n and x_o denote the normalised and original values of x in the input dataset, respectively. $o - min$ and $o - max$ subscripts present the minimum and maximum values of x in both original and normalised datasets. Since, the range of normalisation is [-1, 1], x_{n-min} and x_{n-max} are defined as -1 and 1, respectively. Therefore, the maximum value of the input dataset is normalised to 1, the minimum values is normalised to -1, and all the other values are set to a particular value between -1 and 1. Due to the fact that all the input values are normalised, the outputs of the neural network structure are also fall into a range of [-1, 1]. In this case, the outputs of the neural network system are de-normalised/transformed back into the units of the original dataset in order to use in the following calculation/analysis sections by using the Equation 83.

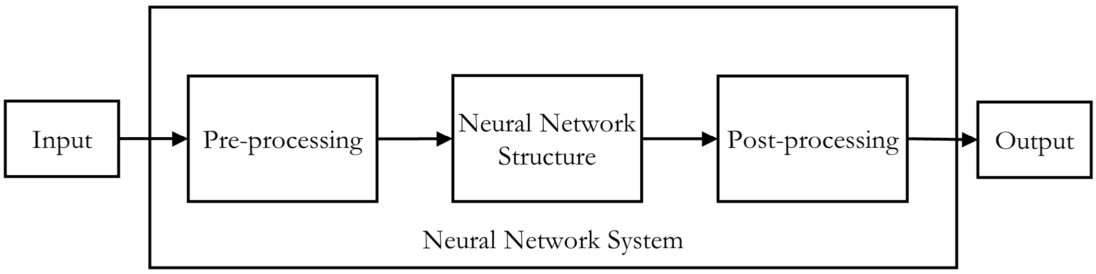
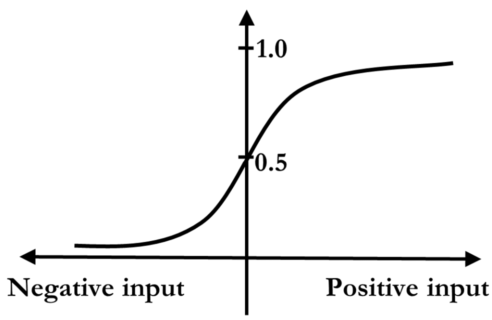


Figure 217: Data pre-processing and post-processing



$$Output_j = \frac{1}{1 + \exp(-Input_j)}$$

Figure 218: Sigmoid function

Data division

There are three stages in the neural network process; training, validation, and testing. In this context, before starting the neural network training, the original dataset has to be divided into three disjoint sets: training set, validation set, and test set. The network weights, biases are updated and the gradients are computed by using the training set. In the validation stage, the validation set is compared with the network outputs whether it performs well enough on an independent dataset. The test set is used to compare the different models; since multiple models may provide sufficient results during training and validation steps. The validation and testing datasets are generally half size of the training dataset (Meyer-Baese and Schmid, 2014); therefore, the first half of the original dataset is set for training, the third quarter and the fourth quarter are employed in validation and testing stages, respectively.

Network training

Mean square error (MSE) value, which denotes the average squared error between the network outputs and the targets, is the main consideration for the assessment of the training process. Equation 84 shows the calculation of MSE.

$$MSE = \frac{1}{n}\sum_{i}^{n}(target_i - output_i)^2 \quad \text{Equation 84}$$

where $n, target_i, output_i$ are the size of population, ith target, and ith output, respectively.

In linear regression, the least square method can be used to define the input weights without any iteration in order to minimise the MSE value; however, it is not possible to define the input weights directly in the case of nonlinear problems. At the beginning of a training, the input weights are assigned randomly; therefore, MSE value is relatively large. In the first order methods, the weights are updated in the direction opposite to the gradient of the objective function. As in Figure 219, if the starting point is at 1, the slope is negative, so the weight has to be increased. If the updated point is at 2, the slope is positive, so the weight has to be decreased. If the updated point is at 3, the slope is also positive, but MSE value is significantly high; therefore weight has to be decreased more than the point 2 in order to achieve the minimum MSE value at w_{opt}.

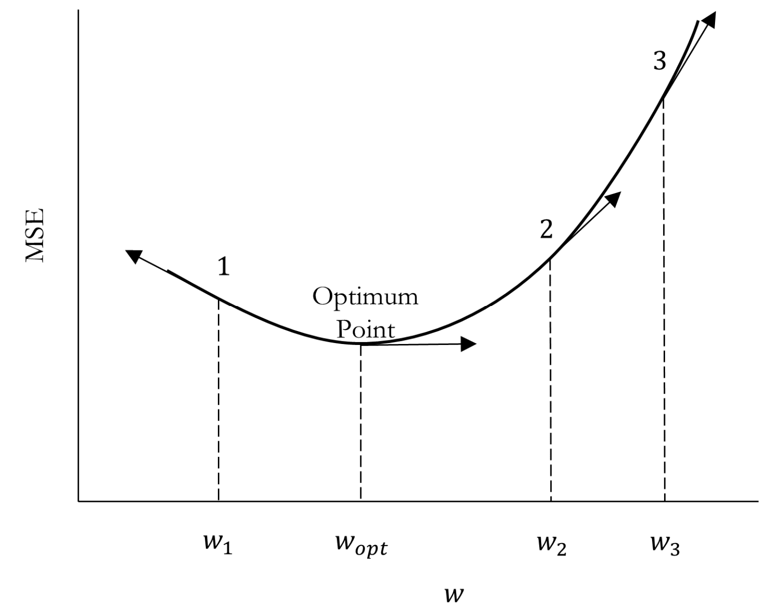


Figure 219: Input weight optimisation

Learning rate shows the size of the shift in the direction opposite to the gradient. As illustrated in Figure 220, if the learning rate is too small, the training may take longer; on the contrary, if the learning rate is too large, the solution may oscillate around the minimum and never reach to it (Smith, 1996).

$$w_{m+1} = w_m + \Delta w_m \quad \text{Equation 85}$$

$$\Delta w_m = -a_m g_m \quad \text{Equation 86}$$

where x_m is the current weights, g_m is the current gradient, and a_m is the learning rate. This equation is iterated until the network converges.

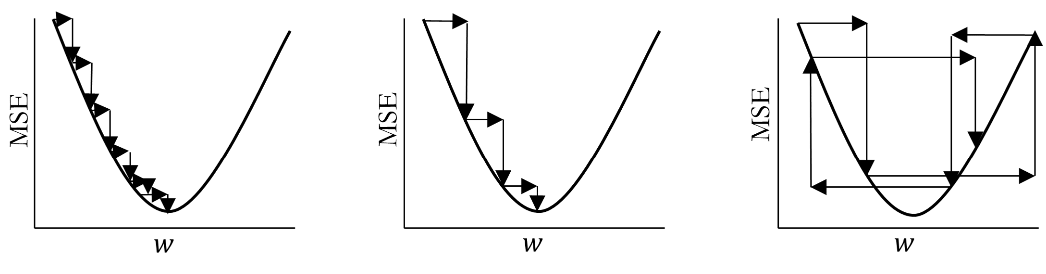


Figure 220: Influence of learning rate

In second-order methods, the curvature of the error surface is also considered in order to achieve the minimum MSE value more efficiently. In this case, the curvature shows the change rate of the slope when the input weights are changed. As in Figure 221, the slope of both curves are equal at the point w_1; however the dashed line leads minimum MSE value quicker than the curve with continuous line.

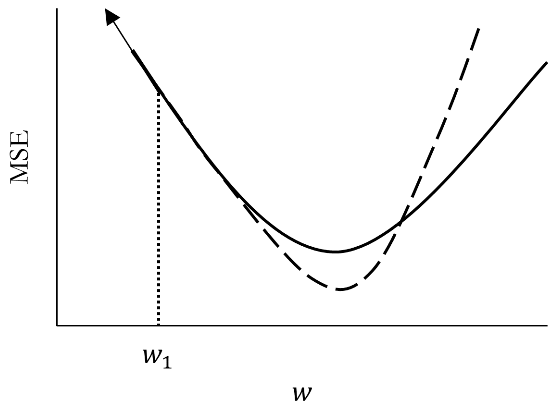


Figure 221: Influence of curvature

The Levenberg-Marquardt and the Gauss-Newton methods are the most common second-order methods of error minimisation (Samarasinghe, 2007). The Levenberg-Marquardt is a standard approach for engineering optimisation problems (Khan *et al.*, 2013); and it is also recommend by Patrick van der Smagt (1994) to reach the global minimum MSE value.

$$w_{m+1} = w_m + \Delta w_m \qquad \text{Equation 87}$$

$$\Delta w_m = -\frac{J^T e}{J^T J + \mu I} \qquad \text{Equation 88}$$

where I is identity matrix, J is Jacobian matrix, e is vector of network errors. In the Levenberg-Marquardt method, the solution converges rapidly to the minimum MSE value. The weights are updated repeatedly by the Levenberg-Marquardt method during the training process in order to improve the performance of network. Each pass through the training data is called epoch, and neural network learns through the overall change in weights accumulating over many epochs.

The training of the network stops under particular situations below;

- If the number of epochs (iterations) reaches to the maximum number of epoch number set by the user,
- If the MSE value becomes equal to the target MSE value set by the user,
- If the validation error increases or remains at the same level for the consecutive number of epochs set by the user

Network validation

Basically, the training and the validation stages are proceeded simultaneously. After finalising the training of a network, the model should be validated whether it performs well enough on an independent dataset. If the model is too flexible, the network fit results in noise and over-fitting, which leads the network to memorise the training set but perform very poor on the validation dataset. On the other hand, if the model is not flexible enough, it may not able to represent the essential characteristics of the dataset, which is also called under-fitting. In order to prevent over-fitting, the error on the validation dataset is recorded during training stage; and if the error starts to increase on the validation set, even though the training error continues decreasing, the training stops. This is because, the network starts to over-fit on the training set; on the other hand, the network loses the flexibility to represent validation set.

Network testing

After validating the network on an independent dataset, testing is required in the case that different weight and bias combinations can produce the desired outcome. Similar to the validation stage, defined solutions are tested in an independent dataset and the best network structure is identified depending on the level of network flexibility.

Appendix B references

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