FLOWDECON

FLoating Offshore Wind DEvelopment CONcept: A sustainable O&M approach

Thesis report

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TU Delft

Royal IHC

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Thesis for the degree of MSc in Marine Technology in the specialization of *Ship Design*

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FLoating Offshore Wind DEvelopment CONcept: A sustainable O&M approach

By

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TU Delft

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Preface

This thesis on the two major component replacement strategies for the floating offshore wind industry was written as graduation assignment for the master Marine Technology at the Delft University of Technology. This assignment was executed at Royal IHC in Kinderdijk as graduation assignment for the MSc. Marine technology at the Delft University of Technology.

First, I want to thank my company supervisor Kevin Runge for all his support, time and enthusiasm during the whole process. The frequent discussions and proofreading provided a critical reflection on the subject and helped me to retain a clear aim of the research. In addition to this I also want to thank everybody at IHC for the pleasant open work environment, where I felt in place from day one.

Secondly, I want to thank my university supervisor Prof.ir. Hopman for his time and critical questions during the regular meetings. These critical question revealed more than once additional aspects that should be covered in the research. I also want to express my gratitude to the secretary of the marine technology department for all scheduled appointments and process related information.

Lastly, I want to thank my family and friends, and most of all my girlfriend, for their support.

Bert-Jan van Wilgen
Breda, August 2022

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Abstract

This research examines the difference between two major component replacement strategies for the novel floating offshore wind turbines (FOWT), in terms of support vessel CO_{2eq} emission and cost together with FOWT downtime. The first strategy is utilising a crane vessel to replace a component in offshore, this is called the heavy lift maintenance (HLM) strategy. The other strategy is the tow to port maintenance (TTPM) strategy, where the floating offshore wind turbine (FOWT) is towed to port to be serviced. Royal IHC is looking for a reliable and relatively quick method to determine the potential of both strategies and test new vessel and equipment concepts, which will allow a head start in this upcoming maintenance market.

To determine the three output parameters; CO_{2eq} emission and cost originating from the support vessels and FOWT downtime, a calculation model has been developed, as this was not available. The calculation model compares seven different support fleet configurations for the two maintenance strategies. The configurations contain at least one heavy lift vessel (HLV), platform supply vessel or anchor handling supply vessel type, which are varied in this study on their empirical based parameterised designs. The calculation model also allows the possibility to include, amongst others, preventive maintenance, breakdown maintenance and utilization of different fuels. In total three FOWT farms, varying in size and distance from shore, were considered to determine the effect of those parameters on the different support fleet configurations.

The calculation model was verified and provides a reliable and relatively quick method to compare different support fleet configurations, concerning the two major component replacement strategies. With the use of this model it was found that the most sustainable support fleet configuration for both preventive and breakdown maintenance is a standalone HLV. However, this conclusion does not hold for full blade replacement campaigns. The cost of this HLM strategy is relatively high compared to the TTPM configurations, especially when considering preventive maintenance campaigns. Therefore, it is suggested that the TTPM strategy is preferred for preventive maintenance campaigns. It must be noted that this is also based on the assumption that the port of repair has unlimited facilities to replace the components as soon as the FOWT arrives. It should also be noted that the FOWT downtime is greater for the TTPM strategy, which could be a potentially important aspect of the repair. The calculation model also allows to test new innovative concepts, such as a quick mooring (dis)connection system and the climbing crane. Both show to have a beneficial effect on the replacement operation.

This research has shown that the developed calculation model is well suited, reliable and a relatively quick method determine the potential of both strategies. This research already provided Royal IHC insight into the new market, but can also be used to inform clients who request an advice. The flexibility of the model allows it to be used for different field, fleet and vessel parameters. Moreover, due to the modular programming method additional information can be added at a later stage. This also leads to some recommendations for further research. A suitable weather module has to be introduced in order to get a better estimation on the vessel downtime. After this is done the program should be optimised in terms of runtime efficiency, in such a way that a Monte Carlo method could be run. The added value of this method is that a more accurate support vessel downtime can be estimated. It is also recommended to include bunker time into the calculation as it is currently set to 0 h and potentially leads to an overoptimistic outcome. Lastly, two other floater types should be designed for a 15 MW turbine and included in the model. These floater types are the tension leg platform and barge floater.

Contents

Nomenclature

Abbreviations

Abbreviation	
AHTS	Anchor handling tug supply
DD	Direct drive
DP	Dynamic positioning
FOWT	Floating offshore wind turbine
GB	Gearbox
GHG	Greenhouse gas
HLM	Heavy lift maintenance
HLV	Heavy lift vessel
HVAC	Heating, ventilation, air conditioning
lcb	longitudinal centre of buoyancy
LHV	Lower heating value
LNG	Liquefied natural gas
MGO	Marine gas oil
NREL	National renewable energy laboratory
O&M	Operation and maintenance
per	Pollutant emission ratio
PRNG	Pseudo random number generator
PSV	Platform supply vessel
SOV	Service operation vessel
SPAR	Single point anchor reservoir
TLP	Tension leg platform
TTPM	Tow to port maintenance
WT	Wind turbine

Definitions

Definition	
Cost	The cost derived from the Royal IHC in-house cost estimation tool. This tool only considers vessel aspects and does not include FOWT aspects. The cost is expressed in € per MWh produced by the wind turbine over its complete lifetime.
Energy demand	The energy demand is the energy demand derived from the vessels operations. This is expressed in kWh per MWh produced by the wind turbine over its complete lifetime.
Failure	The occurrence of breakdown of such kind that the component replacement is required. After a failure the wind turbine can not produce power, until it is repaired.
FOWT downtime	The time between the FOWT component failure and the repair, where after it is back operational and capable of producing power.
HLM strategy	The maintenance strategy where the FOWT stays in the field and the components are replaced by a HLV.
Hs	The average wave height, from trough to crest, of the highest one-third of the waves.
Point based design	A parametric vessel design, based on one key parameter. The point based design provides a general outline of how the vessel should look.
Sustainability level	The sustainability level is measured in g CO_{2eq} emitted during the replacement operation(s) per MWh produced by the wind turbine(s) over its complete lifetime.
TTPM strategy	The maintenance strategy where the FOWT is towed to the O&M port to replace the components by a port crane. After this is finished the FOWT is towed back to the field where it will be moored again.
Vessel downtime	The time that a vessel is operational, but can not perform any operations. This can be caused by for example by bad weather.

Symbols

Symbol	Definition	Unit
$1{+}k_1$	form factor	
A	Weibull scale parameter	
A_{BT}	Transverse bulb area	m^2
A_T	Transom area	m^2
A_{wind}	Cross-sectional area through which air moves	m^2
B	Weibull shape parameter	
B	Breadth	m
BP	Bollard pull	t
C_B	Block coefficient	
C_D	Power coefficient	
C_f	Capacity factor	
C_F	Friction resistance coefficient	
C_M	Midship section coefficient	
CO_{2eq}	Carbon dioxide equivalent	
C_P	Prismatic coefficient	
C_{WP}	Waterplane area coefficient	
E_{tot}	total energy demand	kWh
H_s	Significant wave height	m
L	Length between perpendiculars	m
L_{wl}	Length of the waterline	m
m_{pe}	Total weight emitted CO_{2eq}	
$\bar{\mathbf{M}}_t$	Transition matrix	
N_R	Pseudo random number	
P_B	Brake power	kW
P_D	Power delivered to all the propellers	kW
P_{wind}	Power in wind	kW
R(t)	reliability function	
R_A	Model-ship correlations resistance	kN
R_{APP}	Appendage resistance	kN
R_B	Bublous bow resistance	kN
Re	Reynold number	
R_F	Frictional resistance	kN
R_{TR}	Immersed transom stern resistance	kN
R_W	wave making/breaking resistance	kN
S	Wetted area of the hull	m^2
S_{APP}	Wetted area of the appendages	
$\mathbf{s}_n$	The nth state factor	
t	Time step	h
T	Draught	m
u_{wind}	Wind speed	m/s
Δ	Displacement	m^3
η_{conv}	Power converter efficiency	
η_{distr}	Distributive network efficiency	
η_{em}	Electrical motor efficiency	
η_{gen}	Generator efficiency	
η_p	Propulsor efficiency	
η_{trans}	Transformer efficiency	
η_{TRM}	Transmission efficiency	
λ	Failure rate	failures/year/turbine
ρ_{air}	Air density	kg/m^3
υ	Kinematic viscosity	mm^2/s

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1
Introduction

1.1. Background

Climate change and sustainability are subjects which play a bigger role in our lives every day. The increase in greenhouse gas emissions (CO_{2eq}) could lead to more wildfires, droughts and an 18% decrease in GDP of the world economy, according to the European Commission and the World Economic Forum [19][46]. To avoid these disastrous effects a worldwide commitment to reduce greenhouse gas emissions, and thus becoming more sustainable, has been established in the 2015 Paris agreements. This agreement calls for an increase in renewable energy sources such as wind energy [65]. Wind energy is converted to electrical energy by wind turbines, which are conventionally placed on or near shore. However, both variances face limitations like limited space or large water depths. A variance that avoids these constraints is the novel option; the floating wind turbine [10].

The novel option unlocks not only new deep-water areas for wind energy production, but also demands a new maintenance strategy for major component replacements such as blades or generators. The turbines can be towed to port by ocean going tug vessels or be serviced in field by a crane vessel. These are called the tow to port maintenance strategy and the heavy lift maintenance strategy respectively [44]. However, in light of the growing sustainability ambition it is important to compare both strategies on the potential CO_{2eq} emissions originating from the maritime operations. Especially as recent studies show that the fuel consumption of the support vessels during these operations is an environmental impact hotspot [21]. Moreover, a lower sustainability level can influence the price in a negative way as the greenhouse gas emissions allowances expand to the maritime industry [35]. This also indicates that cost is another important aspect to consider when comparing the different strategies. It is thought that the tow to port maintenance operations are of relatively lower cost, but are more complex and time consuming compared to the heavy lift maintenance strategy.

Royal IHC is interested in the potential and challenges of both major component replacement strategies. However, it remains unclear what the exact differences are between the two strategies considering different project scenarios. Mainly, the sustainable aspect and the cost of the operations are thought to become more important in the near future. Therefore, a Python calculation model is developed to test different support fleet configurations and vessel designs, and compare them on CO_{2eq} emissions and operational cost. This calculation model can be used to provide new insights and test new concepts. It allows Royal IHC a head start in vessel concept design and product development for this upcoming maintenance market.

1.2. Aim of this research

The goal of this research is to gain new insights in the cost and sustainability level (i.e. greenhouse gas emission) of the tow to port maintenance strategy and the heavy lift maintenance strategy operations and the relation to each other for the floating offshore wind industry. This leads to the following main research question:

Main research question:

What is the most effective maintenance strategy, in terms of sustainability and cost, for major component replacements in a floating offshore wind farm?

This main research question includes multiple aspects of the problem, which are covered in different sub-questions, stated in the next section. To answer this main question a calculation model is developed, which allows to test different support vessel configurations and new innovative concepts. An important aspect of this model is covered in the first sub-question and determines how the support vessel designs can be parameterised and varied for the different strategies. The second sub-question is used to verify the model before it is used in the analysis. The third sub-question compares different support fleet configurations of the heavy lift maintenance strategy in terms of cost and level of sustainability. In this comparison the support vessel designs are varied in accordance with the findings in the first sub-question. The same method is performed for the tow to port maintenance strategy in sub-question four. The fifth sub-question will compare the outcomes of the two strategies and sets out the potential benefits if the strategies were combined.

Sub-questions:

1. *How can the generalised concept designs of the support vessels be presented in a parametric manner?*
2. *How can the model that is used for finding the most effective solution of the combined maintenance strategies be verified?*
3. *What is the most effective solution to improve the sustainability of major component replacements in a floating offshore wind farm, considering utilisation and parametric design of support vessels used in the heavy lift maintenance strategy?*
4. *What is the most effective solution to improve the sustainability of major component replacements in a floating offshore wind farm, considering utilisation and parametric design of support vessels used in the tow to port strategy?*
5. *What is the most effective solution to improve the sustainability of major component replacements in a floating offshore wind farm, considering utilisation and parametric design of support vessels used in the combined maintenance strategies?*

1.3. Structure of this report

The body of this report is structured around the sub-questions mentioned in the previous section. Moreover, a literature study was conducted in advance, of which a summary is provided in chapter two. The literature study also laid the basis for the research objective of this study, which is provided in chapter three, together with the research methodology for this report. Chapter four describes the developed calculation model in detail and also provides an overview of the different support fleet configurations that are used throughout this report. The calculation model is first verified in chapter five before it is used for further strategy analysis. A sensitivity analysis to test and verify the quality of the outcomes of the calculation model is also included. The second and third sub-question are covered in chapter seven and eight, respectively. Chapter nine compares the different strategies, thereby answering sub-question four. Additionally, it also provides insight in what the potential effects of new technologies or legislation will be. These effects are determined by the same calculation model that is used in chapter seven and eight. The information found in this report provides the answer to the main research question and is summarised in chapter ten. The final chapter provides suggestions for further research.

2 Literature study

2.1. Introduction

The complete research consists of two parts; the initial literature study and the master thesis (this report). The initial literature study has been finalised and presented on the 21st of February 2022. The aim of that report was to find an effective solution to increase the sustainability of the maritime support operations in the floating offshore wind farms life cycle. Findings of the literature report are used as a factual basis for this report and are presented in this chapter. Note that findings in this chapter can be open for revision due to new insights. Insights that result in alteration of these findings will be further explained in this report.

2.2. Literature study

The literature study was written to gain theoretical background into the sustainability level of floating offshore wind farms and which potential improvements, related to the support vessels, are possible. This was established in an elaborate problem statement, which has been converted into the following main question for the literature research:

Main literature research question:
What is the most effective solution to improve sustainability in the floating offshore wind farm life cycle, regarding the support vessel operations and designs?

To start with, the different life cycle phases were studied. There are five distinct phases in the life cycle of a floating offshore wind farm, which each have their own operational challenges. First, the development and consenting phase is performed. This phase is used to select an appropriate site, where after the project can be brought to a public commercial bidding-market during the tender procedure. Next, the production and acquisition phase is entered. During this phase raw materials are gathered, which will be used to manufacture the floating offshore wind turbine (FOWT) components. Then the installation is carried out, during the installation phase. Mooring systems are prepared and the FOWTs are assembled onshore, nearshore or offshore in situ. The installation phase is finalised after the commissioning tests are performed and accepted. In the following step the FOWT farm starts to produce energy and enters the operation and maintenance (O&M) phase. The maintenance has to be carried out during this phase to maintain the energy production. The maintenance operations can be categorised in minor or major. The minor maintenance operations are performed by FOWT technicians without additional assistance of large or heavy cranes. Typically, the technicians are brought to the site by a crew tender vessel or a service operation vessel. The major maintenance operations on the other hand require a large or heavy crane to replace the heavy components, like the gearbox, generator or blades. The replacement of major components can also be performed onshore, nearshore or offshore in situ. The final life cycle phase of a FOWT farm is the disassembly phase, where it is disassembled. The disassembly can also be carried out onshore, nearshore or offshore in situ and is broadly speaking the reversed installation process.

Secondly, a quantifiable definition on sustainability was drafted, which allowed for unambiguous comparison between different FOWT farms. The appropriate definition for sustainability was found to be g CO_{2eq} per kWh produced by the FOWT farm, during its full lifetime. This definition is based on the interpretation and prioritisation of different stakeholders in the floating offshore wind industry. This definition is also used in various life cycle studies and allows for direct comparison between different FOWT farms.
With the use of this definition it became clear that the largest negative contribution to the level of sustainability originates from the production and acquisition phase. However, most of this contribution cannot be traced back to maritime (transport) operations. The second largest contribution is made by the O&M phase or more precisely the O&M vessels. Therefore, the most effective solution to improve the level of sustainability is sought in this phase. Especially, the major component replacement operations are considered to be the best suited for effectively reducing the greenhouse gas (GHG) emissions, as FOWTs allow alternative major component replacement strategies.

Thirdly, key utilisation and design aspects of the support vessels were determined for the improvement of the level of sustainability. The utilisation of the support vessels is based on the two different major component replacement strategies, also referred to as O&M strategies. These strategies are called to the tow to port maintenance (TTPM) strategy and the heavy lift maintenance (HLM) strategy. During the TTPM method the FOWT is towed to a maintenance port or nearshore area for major component replacement. Whereas the HLM method uses a heavy lift vessel (HLV) in situ to replace the major components. It is expected that both strategies will be used in a hybrid manner for future FOWT farms. The support vessel design aspects that can improve the level of sustainability are lower ship speeds, the use of alternative fuel with lower pollutant emission ratios or exhaust treatment. The reduction in ship speed will only be viable to a certain extent as operations still have to be performed within a certain time frame.

Lastly, key drivers were identified together with potential calculation methods. The key drivers can be categorised into three different categories; external factors (external drivers), support vessel utilisation (operational drivers) and support vessel design (design drivers). The maintenance request, preventive or corrective, is the actuator of the maintenance task. The preferred calculation method will verifiably calculate every outcome in the provided specific range. The essential comparing criteria are the level of sustainability and FOWT downtime or specific vessel operational duration. The FOWT downtime or specific vessel operational duration both counteract the level of sustainability.
Additionally, a simplified case study was performed for the Hywind Scotland project. This showed that for the replacement of four generators and 15 blades, the HLM strategy was the fastest approach, but far less sustainable in comparison to the TTPM strategy.

2.2.1. Reflections on the literature study

In the literature research it was also decided that the outcomes would best be compared in an analytical hierarchy process after the model has completed all calculations. While this would be an appropriate tool, it is decided not to include this in the research. The main reason is that no suitable specialists were found to prioritise the outcomes. Without this proper and well informed prioritisation, the AHP loses its value and is therefore excluded. Instead, the outcomes are exported in an excel format, which allows descriptive comparison. Another aspect that is excluded is the variable engine efficiency as this would result in a factor increase of the already significant amount of data. This could potentially mute, or muffle, interesting differences between the strategies and support fleet configurations. Still, the model is programmed in such way that at a later stadium the variable engine efficiency could be implemented.

3 Research methodology

3.1. Introduction

This chapter provides insight in and reasoning behind the research methodology that is applied for this research. First, a brief recap is given of the research gaps that were found during the literature research. Next, these research gaps are translated into the research objectives and supplemented by the vision of Royal IHC. Lastly, the research methodology is discussed to provide better understanding of the decision and aim of the calculation model that is developed to achieve the research objectives.

3.2. Research gap

The new industry of floating offshore wind allows for new possibilities for major component replacements. Nevertheless, this also results in research gaps as the new strategies have to be analysed and compared before the actual advantages and disadvantages can be determined. Based on the growing sustainability and expansion of the emission allowances it is decided that the GHG emission is one of the main topics of this research. However, another aspect is the cost of the major component replacements operations. This is chosen as an important aspect as the delivery price of FOWT energy is estimated to be twice the amount of fixed offshore energy [58]. The literature study provides two research gaps which are covered in this report.

3.2.1. Optimum major component replacement scenario remains unclear

It was found that there is currently no method that is able to provide an optimum number of vessels to deploy for major component replacement scenarios. Different strategies and support fleet configurations can be compared with the use of extensive O&M tools, which are commercially available. However, every variance in ship design or strategy would require a remodelling step of the O&M tool, followed by a new run of the model. Moreover, the outcomes are compared descriptively and often only provide either the cost or the normalised GHG emissions.

3.2.2. O&M strategies are not combined in calculations

Research from the Carbon Trust suggests that the TTPM and the HLM strategy will be used in a combined, hybrid, manner [63]. Despite this suggestion there are no literature sources found that determine the level of sustainability which includes the hybrid strategy. The Carbon Trust report and the report of the Offshore wind innovation hub do include cost calculation for what is most suitable for single FOWT repairs or a full maintenance campaign, but this is not extended to the complete FOWT operational lifetime [28].

3.3. Research objectives

The objective of this research is to determine the most effective maintenance strategy, in terms of sustainability and cost, for major component replacements in a floating offshore wind farm. This includes the comparison of different support fleet configurations and a large range of parameterised vessel designs. Moreover, it should be able to include hybrid replacement campaigns for both preventive and breakdown maintenance. This does also align with the vision of Royal IHC.

3.3.1. Vision of Royal IHC

Royal IHC aims to gain more knowledge on the benefits and drawbacks of the different major component replacement strategies, in terms of cost and sustainability. This will in particular include the hybrid maintenance strategy as this is suggested to be more beneficial compared to a strategy that solely relies on just one of the two concepts. Royal IHC is also interested in a relatively quick and easy method to get an initial idea on the cost and sustainability for different FOWT projects. These different projects will have different farm parameters, like distance from the O&M port or power output, and those should also be included as a variable in the calculations. Lastly, it would be interesting to see the potential of new innovative concepts or legislation in the FOWT industry. These research objectives provide Royal IHC a head start in vessel concept design and product development for this upcoming FOWT maintenance market.

3.4. Research methodology

3.4.1. Methodology background

The literature study that was performed in advance of this study, is summarised in the previous chapter. This relatively broad study created the basis for this research, but also showed where the research gaps currently are. From these research gaps the research objectives were derived and supplemented by the vision of Royal IHC as discussed in the previous section. It is deemed necessary to develop a calculation model which has to allow for the potential variance in key drivers for the different FOWT farms and strategies. A calculation model provides a method to compare a large number of different support fleet configurations (including vessel design) on different FOWT farms, in a relatively short time span.

3.4.2. Programming language

The calculation model is created in Python, which is a free general-purpose programming language [51]. This language was chosen as the preferred language, because Royal IHC is already familiar with Python.

3.4.3. Essence of the calculation model

The calculation model utilises point based vessel designs derived from key parameters and is based on different databases. More information on these point based designs can be found in chapter 5. These vessels are used in different support fleet configurations and are varied on their key parameters. These are implemented in the model and form the core of the simulation model. Each simulation step can be separated into two different aspects; the time aspect and the energy demand aspect. Note that both aspects are present for both the preventive and breakdown maintenance. The time aspect covers the operational duration of a vessel, for if a vessel was to conduct a certain operation. This time duration will mainly influence the cost of the operation and FOWT downtime. The other aspect depends on the energy demand a vessel requires in a certain operational profile. This also depends on the vessel design as, in general, larger vessels have a higher energy demand. Note that the energy demand is used to determine the GHG emissions. Eventually the energy demand and the time combined give the power demand for the entire maintenance operation. The operations that are considered to be a simulation step are transit, towing, port idle, dynamic positioning (DP) and DP in combination with crane usage.

3.4.4. Calculation model output

The model includes a large number of key drivers, which were identified in the literature study. The most vital key drivers are shown in table 3.1. The amount of data that can be extracted for a scenario is relatively diverse and can be categorised in vessel-level data and strategy-level data. The vessel-level data consist of vessel specific data, for example the fuel consumption distribution over the operational profiles for a single vessel. The strategy-level data are the highest level data and provide information on how well a strategy performs. An example of strategy-level data is the fuel consumption on the entire replacement operation(s), which is the addition of the vessel-level data. This report will mainly focus on strategy-level data as different scenarios are compared. However, it must be noted that the vessel-level data also change as these are part of the strategy-level data. The strategy-level data that will be included in this research are the energy demand, cost and FOWT downtime. This data will be generated for three different FOWT farms varying in farm size and distance from the O&M port.

Table 3.1: Key drivers

Input variables		
External drivers	*Operational drivers*	*Design drivers*
Component failure rate (breakdown maintenance)	Component replacement time in field	Engine efficiency
Distance between O&M port and the FOWT farm	Component replacement time in port	Fuel type selection
Distance in between FOWTs	Mooring hook off time	Point based design of support vessels
Floater type	Mooring hook on time	Power demand in operational profiles
Number of mooring lines per FOWT	Towing speed	
Operational lifetime	Transit speed	
Preventive maintenance		
Rated turbine power		

4

Model description

4.1. Introduction

In the previous chapters it is decided that a calculation or simulation model is needed to include the potential variance in key drivers for the different FOWT farms and strategies. All the specified key drivers are implemented in the model and discussed in this chapter, apart from the support vessel design drivers which are discussed in the next chapter. This chapter starts with a global description of the model, providing a better insight in how the different modules are connected to each other. Secondly, the modules, such as the weather module and support vessel strategy module, are explained in more detail and the reasoning behind the assumptions made is provided.

4.2. Overview of method

The model consists of six successive modules, which are required to calculate the CO_{2eq} emissions originating from fuel consumption by the support vessels, the FOWT farm power output, the FOWT farm downtime and the support vessel cost of multiple strategies. The first module concerns the weather and in this module a timeline for the expected lifetime of the FOWT farm is generated. This weather timeline takes into account the wind speed and significant wave height at an appointed geographical location. In the second module the wind turbine (WT) models are implemented into the weather timeline. In this module the operational time of the FOWT farm is determined as a whole and the capacity factor is calculated. The operational time is the time that the FOWT farm produces energy. In the third module the amount of failures of the FOWT components is determined. Additionally, preventive maintenance on the FOWTs was implemented. The fourth module concerns the different O&M strategies that are selected and the amount of energy required is determined. Also, the downtime of the FOWT resulting from the chosen strategies is generated. In the fifth module the different (alternative) fuels, that can be used by the support vessels to generate the required energy for the replacement operations, are implemented. The choice of fuel will have impact on the CO_{2eq} emission, together with the potential autonomy of the vessels. In the sixth module a cost estimate for each of the chosen O&M strategies is provided. Note that this module only considers the cost of the utilisation of the support vessels. A compact visualisation of the different modules is provided in the figure below. A more elaborate visualisation can be found in appendix A.

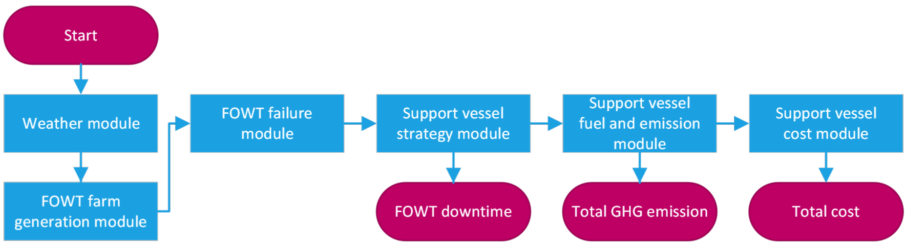

Figure 4.1: A compact model visualisation.

4.3. Floating offshore wind turbine models

4.3.1. Reference wind turbine

It was decided, based on the recent trends found in the literature research, that a 15 MW turbine will be representative for the calculation model. These turbines are designed by, amongst others, GE Renewable Energies, Siemens Gamesa Renewable Energy and Vestas [45]. The offshore wind market is very competitive and actual data regarding these turbines is hard to come by. Fortunately, there is a technical report available from 15 MW reference offshore WTs, by the national renewable energy laboratory (NREL). Detailed specifications on this turbine design can be found in appendix B.

Power curve

The energy yield from a turbine depends on the available power in wind (P_{wind}), which can be calculated with equation 4.1. The available power of the wind is related to the cross-sectional area through which the air moves (A_{wind}), the density of the air (ρ_{air}) and the wind speed (U). An interesting remark here is that a doubling in rotor diameter leads to a quadruple increase in wind power [25].

$$P_{wind} = \frac{1}{2} \cdot A_{wind} \cdot \rho_{air} \cdot U^3 \tag{4.1}$$

However, the wind power does not match the actual power output, with the latter being lower. A way to create a theoretical correlation between the wind speed and power output is the WT design specific power curve. This starts at the cut-in wind speed. This is the lowest wind speed at which the WT starts generating energy. With an increased wind speed the energy production increases as well, up to the rated wind speed. The rated wind speed is the wind speed at which the energy output is at its maximum. When wind speed increases, it will reach the cut-out wind speed. The wind speed at this point would create too much load on the structural capacity of the WT if it would remain operating. Therefore, the WT stops producing energy [25]. The cut-in, rated and cut-out wind speeds are provided in appendix B and used to create the theoretical power curve which can be seen in figure 4.2. The power function from the cut-in speed to the rated wind speed is assumed to be a quadratic function.

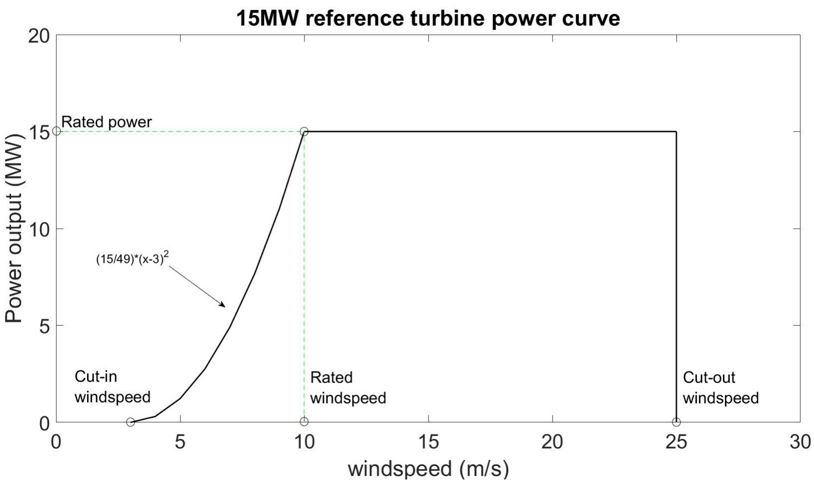

Figure 4.2: Power curve based on 15 MW reference OWT specification [20].

With the power curve and the weather timeline known, it is possible to calculate the capacity factor (C_f). The capacity factor is the ratio between the maximum power output a WT can generate over time and the actual power output during the same time span. Note that this is not the same as an efficiency factor [25].

Major components

The weight of the components is an important parameter for component replacement, especially for the HLM strategy. The weight of the components can vary between WT designs and is often not publicly available. Overall replacement time of a major component by crane, either on shore or offshore, is estimated to be 52 hours, which is in accordance with ”Reference Cases for Verification of Operation and Maintenance Simulation Models for Offshore Wind Farms” [16].

Direct drive
The dimensions and weight of the generator are available for the 15 MW NREL reference WT. This concept is a direct drive (DD) generator [20]. This means that there is no gearbox in place and the shaft from the hub is directly connected to the generator, without intervention of a gearbox (4.3). However, this does result in high torque requirements, which lead to significant larger and heavier generators compared to the geared generators [17]. The weight of the DD generator in the reference WT is 371 t and comes down to 45.3% of the total nacelle weight. The diameter of the generator is 10.53 m and is directly placed behind the hub. This location leads to hindrance in replacement as all blades and the hub have to be removed before the DD generator can be replaced. Despite this replacement time is still set to 52 h as no other information on this subject was found.

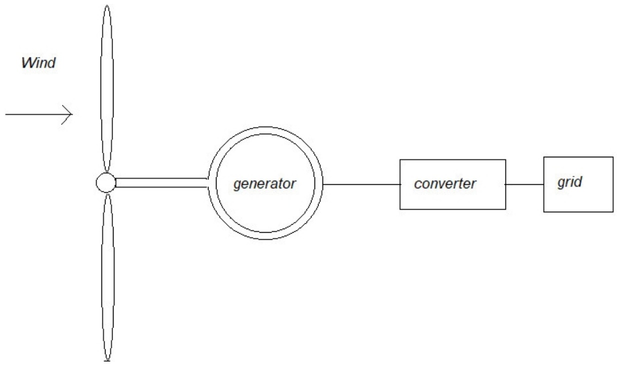

Figure 4.3: The direct drive setup [17].

Gearbox-generator drive
The gearbox-generator (GB generator) is connected to the hub via a gearbox. This allows the generator to be smaller and lighter compared to the DD generator. There is no 15 MW reference WT available which uses a GB generator, as shown in figure 4.4. Hence, an assumption has to be made to estimate the weight. The LCA paper from 2013 of Arvesen et al. approximates the gearbox weight at 13.8% and the generator weight at 34.4% of the nacelle weight [5]. Whereas another study from S. Wang et al. assumes that the gearbox takes up 19.9% and the generator 27.3% of the total nacelle weight [69]. The ”Wind turbine-materials and manufacturing fact sheet” from D. Anacoda makes the assumption that the gearbox and generator both are $\frac{1}{3}^{rd}$ of the total nacelle weight [4]. In conclusion, the papers do roughly agree on the generator weight, but the difference between gearbox weight estimations is more than 20% of the nacelle weight. From a conservative point of view, it is chosen that the fact sheet from D. Anacoda will be used for further calculations. An additional assumption is that the nacelle weight of the DD is equal to the GB generator drive. This leads to an approximated gearbox and generator weight of about 275 t.

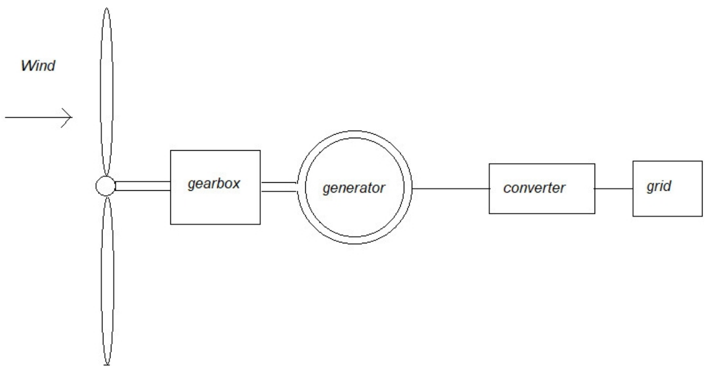

Figure 4.4: The gearbox-generator drive setup [17].

Blades
The blades from the reference WT are 117 m long, with a maximum flange diameter of 5.10 m. There are three blades per turbine, which have an individual weight of 65 t.

4.3.2. Floaters

The reference WT was initially designed as a fixed offshore WT, but a continuation on the study applies two different floating substructures. These are the WindCrete and ActiveFloat platforms, a single point anchor reservoir (SPAR) floater and semi-submersible floater design respectively. In appendix C, both concepts are explained in detail. It should be noted that the FOWT concepts are designed based on the Canary Island site. The limitation at this site is that the hub height is constrained to 135 m. This reduction does not have any influence on the design, apart from the reduced tower height [3]. More information on the dimensions of the floaters can be found in appendix D.

4.3.3. Wind farm implementation

To model the complete farm, additional information is needed. The variables that are necessary to define a farm are the number of FOWTs in the farm, the distance from the O&M port, the distance between the FOWTs in the field, the expected lifetime and the geographical location.
In this report three different FOWT farms are created and used for the comparison of different support fleet configurations. The distance from shore and the number of FOWTs the farm possesses are linearly correlated. This assumption is based on the analysis of a recent database of FOWT projects, which shows that there is a trend to place larger FOWT farms further from shore. A scatter diagram of the database can be found in appendix E. The different farms that are considered for this report are named farm A, B and C and posses the properties shown in table 4.1. The distance between the FOWTs is decided to be 2.4 km (1.3 nm) agreeing to the general assumption that the distance between them is approximately between seven and ten times the rotor diameter [25].

Table 4.1: FOWT farm specifications.

Farm	Ref. turbine	# of FOWTS	Distance from O&M port (km)
A	15 MW	10	10
B	15 MW	50	50
C	15 MW	100	100

4.4. Weather module

As stated in section 4.2, the weather timeline is the first module of the calculation model. This module creates a direct link to the operational time of the FOWT farm. Moreover, it provides a limiting factor for the O&M operations, typically characterized by significant wave height and wind speed [23]. A stochastic weather generator which is seen in multiple offshore O&M tools is the Markov chain model. This model is used, amongst others, in the offshore wind O&M models of Tzioiutzias [64] and Huang [27]. Two other models, which also incorporate the Markov chain model for weather generation are validated by M. Scheu [55]. This indicates that this model will be suitable for the calculation model in this report.

4.4.1. Markov chain model

The Markov chain model is a stochastic model, which can be used to describe a sequence of possible events. The state of the process at a moment can not be predicted with certainty, but rather the probability that a given state occurs can be predicted by knowing the state of the system at the preceding observation. The model is a memoryless model, i.e. the future states only depend on the current states [34].

State vectors and transition matrix

The Markov chain is defined by the set of states and the set of transition possibilities. The set of transitions is given in the transition matrix (M_t), which describes the probability of the transition from one state to the other. Note that the sum of each row has to be equal to one, because the probability is 100% [34]. The transition matrix, used in the calculation model of this report, is based on historical

(5 year) ERA5 wind data for a specific geographical location. The first state vector (s_0) is created in a pseudo-random way, with the use of the Mersenne Twister pseudo random number generator (PRNG). Multiplying the first state vector with the transition matrix provides the probability for the different possible wind speeds derived from the ERA5 data in the next time step. The probability of the next state vector (s_n) is compared to a PRNG number, to derive the actual state during the next time step. The state vector for each time step is governed by the transition matrix. This offers the advantage of generating a state vector for every thinkable time step without knowing other time steps, apart from the first [34]. This is also shown in equation 4.2.

$$\mathbf{s}_n = \mathbf{s}_0 \bar{\mathbf{M}}_t^n \tag{4.2}$$

Data implementation in the calculation model
The historical ERA5 wind data in the calculation model go back five years, which is deemed sufficient to mute potential extremes. There are waves generated by the wind, so called wind waves. These waves are very irregular [32]. To still correlate the wind waves to the wind speed, a site specific correlation is drafted. An example of the wind-wave correlation is visualised in appendix F. The time steps this module simulates are one hour and thereby normative for the whole calculation model.
The operational limits during the different operations performed are either set in significant wave height (H_s), wind speed (u_{wind}) or both. The operational limits are provided in the table below and based on the Offshore wind innovation hub report [28]. The H_s operational limits are also valid three hours before start of the operation, as a wave field passage takes about three hours [32].

Table 4.2: Operational limits [28].

Operation	H_{smax} (m)	u_{max} (m/s)
Lift on/off by the HLV	1.5	12
Lift on/off by port crane	x	12
(Un)loading in port	x	12
Hook on/off	1.5	12
Towage	2.5	12

The weather timeline will not be implemented for the comparison of different support fleet configurations. The weather module generates an arbitrary weather timeline, which influences the downtime of the vessels. In theory, the downtime of the vessels can be between zero and infinite hours. This makes comparison between the different support fleet configurations difficult. Moreover, the weather timeline does not converge as weather itself remains a stochastic process. Even if it is decided to take one timeline, the question remains what the added value is of the information found. A Monte Carlo simulation could solve this problem, but that would require a revision of the model to make it more efficient in its calculation time. Currently, the model runs take too long to efficiently be used in a Monte Carlo simulation and specialist programming assistance would be required. This lays outside the scope of this research, and it is therefore decided that the weather module will not be used for the comparison of the different strategies and configurations.

4.5. Failure module

The failure module is the second module in the calculation model. It is used to implement preventive maintenance and generate corrective maintenance tasks. Preventive maintenance is the maintenance that is conducted before failure, in contrast to the corrective maintenance that is performed post failure. The occurrence of a failure is a probabilistic event of which the likelihood depends on many factors, such as the environmental load and the design/manufacturing of a component [53]. The failure module used in the calculation model implements the stochastic behaviour and acts as an actuator for the successive (O&M strategies) module.

4.5.1. Framework

The failure rate of a component (λ) can vary over time (t). New components can have a higher failure rate during the early life time. This is called the brake-in or early life stage and often occurs due to flawed manufacturing or design. This failure rate drops over time to a constant failure rate. This stage is the useful life stage and is the most significant stage for reliability prediction and evaluation activities. The last stage of a component is the wear-out stage, when it starts to wear out or break down, which leads to an increase in failure rate [38]. The three consecutive stages can be plotted in a bathtub curve shown in figure 4.5.

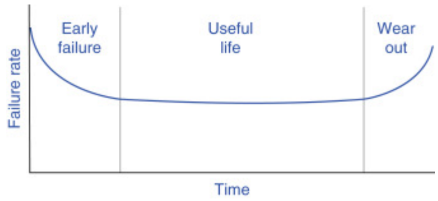

Figure 4.5: Failure rate bathtub curve [38].

However, a prominent paper of J. Caroll, based on empirical data, refutes the idea that all WT components go through this curve and states ”*... turbine sub-systems with higher failure rates, such as the pitch and hydraulic system, do not follow the bathtub curve,..*”. All the major components are components with a relatively high failure rate [8]. Therefore, a constant failure rate is assumed in the calculation model.

Reliability function

The reliability function (R(t)) of a component expresses the probability that the item will not fail at a certain time. This function is described in equation 4.3 for the exponential failure distribution and in equation 4.4 for the Weibull failure distribution. The A and B parameters in the latter equation are the scale and shape parameters respectively. These parameters are component specific [53].

$$R(t) = e^{-\lambda t} \tag{4.3}$$

$$R(t) = e^{-(t/A)^B} \tag{4.4}$$

The reliability function is compared to a Mersenne Twister PRNG, see equation 4.5. If the PRNG number is larger than or equal to the reliability, function failure is simulated at time step (t). In the calculation model t is left out of the equation as the failure rate is assumed to be constant [53].

$$N_R \geq R(t) \tag{4.5}$$

Data implementation in the calculation model

Recent failure data of the different components is not publicly available. Therefore, information from 2016 is used, which describes the failure rate of the components based on a dataset. It must be noted that the data set includes 1768 WTs of which only 350 are located offshore. Moreover, 68% of the WTs included are between three and five years in operation [8]. The failure rates, failure per turbine per year, as provided in the paper are shown in table 4.3. It is assumed that the DD generator failure rate is equal to the GB generator failure rate.
The components that have failed according to equation 4.5 are stored in a data set, together with the time of failure and the possible operational limits for the replacement operations. This data set will be used by the successive module, which assigns a variety of support fleet configurations to the failures.

Table 4.3: Major component failure rate [8].

Component	λ
Direct drive generator	0.095
Gearbox-generator	0.095
Gearbox	0.154
Blade	0.010

4.6. Support vessel strategy module

4.6.1. Vessels included in the configuration

From the literature review, summarised in section 2, it became apparent that two different strategies can be identified; the TTPM and HLM strategy. Both use different kinds of vessels and allow for different support fleet configurations. The vessels that were identified are the (assisting) anchor handling tug supply (AHTS) vessel, the heavy lift vessel (HLV), the service operation vessel (SOV) and the platform supply vessel (PSV). Before a vessel type can be implemented it is necessary to create point based ship designs. More information about point based designs can be found in chapter 5.

It is decided that the SOV will not be included into the O&M strategies. The SOV does normally spend two to four weeks in the field and only visits port for crew changes and bunker intakes [59]. This means that the vessel has exactly the same contribution for all O&M strategies and thus will result in an additional constant. This is avoided by excluding the SOV from the model. Moreover, there are more recent events where SOVs can be electrified. The electrified SOVs are capable of charging at the (FO)WT site with specially developed charging buoys, leading to emission free vessels. These vessels and charging buoys are currently at their highest technological readiness level and commercially available. Suppliers of these buoys and vessels are Royal IHC and a joint venture of Ørsted and Maersk [2]. Therefore, it is decided that the SOVs will not be included into the calculations.

Figure 4.6: An electric SOV at a charging buoy.

4.6.2. Heavy lift strategies

The different HLM strategies are visualised in appendix G.

Configuration 1
The first configuration is the simplest configuration, as it only uses one HLV. The HLV loads the components that have to be replaced on its own deck after which it sails to the field. Arrived at the field it starts to replace the components with its own crane. Once the task is completed the HLV returns to port to unload the replaced parts. This configuration can be used for at least one replacement operation.

Configuration 2
The second HLM configuration is an extension of the first configuration, as it includes a PSV. The role of this PSV is a "feeder vessel". This means the HLV can remain at the field where new replacement components are provided by the PSV that shuttles between the port and the field. The HLV itself also has the possibility to carry some components, so the operational time of the PSV can be reduced. This configuration is better suited for a larger amount of replacements.

Configuration 3
The third and last HLM configuration utilises one HLV and two PSVs. These PSVs have the same role as in the second HLM configuration, but sail in an alternating sequence to the field. The potential advantage of this configuration is that the HLV waiting times in field can be reduced as it does not, or at least to a lesser extent, have to wait for the return of a PSV. This configuration is suitable for two or more component replacements, also depending on the carrying capacity of the HLV. This configuration is better suited for a larger amount of replacements.

4.6.3. Tow to port maintenance strategies

The different TTPM strategies are visualised in appendix H.

Configuration 4
The fourth configuration is the first TTPM fleet configuration and exists of one AHTS vessel and one assisting AHTS vessel. The AHTS vessel is capable of towing the FOWT from and to the O&M port. The assisting AHTS vessel will also transit to the site to hook the FOWT on or off from its mooring system. When the FOWT is in port for repair, the AHTS vessel is port idle. The assisting AHTS vessel can either follow the AHTS vessel along or wait in the field for the AHTS vessel with the FOWT to return. When the FOWT is repaired and hooked on again, the vessels return to port. This configuration can be used for at least one replacement operation.

Configuration 5
The fifth configuration uses the same vessels as the fourth configuration plus an extra assisting AHTS vessel. The assisting AHTS vessel will provide additional help during the hook on/off operations. The outcomes of this configuration should indicate if it is beneficial to add the third vessel, considering the costs, emission and FOWT downtime. This configuration can be used for at least one replacement operation.

Configuration 6
The sixth configuration utilises two AHTS vessels and two assisting AHTS vessels. At first glance, this strategy can be interpreted as a double version of configuration four. However, the vessels will be used in an alternating manner. One AHTS vessel and one assisting AHTS vessel will only hook off FOWTs and tow them to the O&M port, whilst the other AHTS vessel and assisting AHTS vessel only tow them to the field and hook them on. This configuration is better suited for a larger amount of replacements.

Configuration 7
The last and seventh configuration considered uses six vessels, two AHTS vessels and four assisting AHTS vessels. The idea behind this strategy follows the same idea as configuration six. Again the fleet is divided into two groups of one AHTS vessel and two assisting AHTS vessels. Each group either hooks the FOWTs off and tows them to port or tows them to the field where they are hooked on. This configuration is better suited for a larger amount of replacements.

4.7. Fuel and emission module

The fuel and emission module provides the necessary information with regard to the fuel that is selected for a specific strategy. In the literature review five different fuels were selected and are utilised in the calculation model. These fuels are liquefied natural gas (LNG), methanol, hydrogen, ammonia and marine gas oil (MGO). The latter is currently one of the most used fuels in the maritime industry and will serve as a base-line fuel.
From the maintenance request, in combination with the information from the support vessel designs, a total energy demand can be derived. This demand has to be satisfied by the fuel consumption in order to carry out the operations. The amount of fuel consumed depends on the total energy demand (E_{tot}), the lower heating value (LHV) of the fuel and the propulsor efficiency (η_p), which is assumed to be 50 % [42]. Multiplying the fuel consumption with its CO_{2eq} pollutant emission ratio (per), provides the total weight CO_{2eq} emitted (m_{pe}), as shown in equation 4.6.

$$m_{pe} = \frac{E_{tot}}{LHV \cdot \eta_p} \cdot per \tag{4.6}$$

Next to the energy requirement that has to be fulfilled, it is vital to check if the vessels posses the required bunker capacity. Bunker capacity is a vessel parameter, which is discussed in more detail in chapter 5. The different fuels considered require different bunker procedures and bunker times. Moreover, bunker time can vary a lot between regions. It is assumed that the bunker time is equal to zero and can be performed as soon as a vessel visits the O&M port. Note that this assumption can lead to too optimistic port idle times. More research on and implementation of this topic is highly recommended. Specified details on the different fuels are provided in table 4.4.

Table 4.4: Fuel figures [42].

Fuel	GHG (CO_{2eq}/MJ)	Cost ($/GJ)	ρ (kg/l)
MGO	76.4	12.0	0.84
LNG	57.8	9.0	0.43
Methanol	70.3	26.3	0.79
Hydrogen	0.0	26.3	0.07
Ammonia	5.3	26.3	0.76

4.8. Cost module

The cost module is the last module that is passed, which is based on a Royal IHC in-house cost estimation tool. The module works in two different steps. First, the capital expenses of the vessel are estimated based on the hull, outfit, accommodation, electrical and heating, ventilation, airconditioning (HVAC) cost. Additionally, mission equipment is included and specified for each vessel type. Machinery cost, which are specified for different fuel types, are also included in the capital expense calculations. The second step uses the capital expenses of the vessel to determine its depreciation. This information is combined with the fuel, maintenance, crew and insurance cost to determine its hourly rate. This rate is multiplied with the time the vessel is active in the model to get the total cost over the lifetime of the FOWT farm.

4.9. Output variables

The model can provide the user with a large variety of data. However, not all data is as relevant or useful. The main output parameters of the model used in this report are presented below.

4.9.1. Greenhouse gas emission

The GHG emission, expressed in CO_{2eq}, is the most important parameter as this indicates the level of sustainability, as decided in the literature research. GHG emission is caused by the fuel consumption of the support vessels to meet their energy requirements. As discussed before, the different fuels lead to different GHG emissions. To compare the different maintenance tasks for the different fields it is decided that the GHG emission is provided in CO_{2eq} per MWh generated by the number of FOWTs that undergo component replacement.

4.9.2. Wind turbine downtime

The downtime of the FOWT is the time it takes between breakdown and coming back into service. Downtime is only considered for the breakdown maintenance request and not for the preventive maintenance request. This is based on the assumption that the FOWT is switched off as soon as the HLV arrives at the FOWT and is in DP or starts to be hooked off by the assisting AHTS. In the literature the lift off and lift on operations combined on site are estimated to take between 48 h and 52 h [28][16]. From a conservative point of view it is decided that 52 h will be used in this report. This means that the FOWT downtime for the HLM is 52 hours and the downtime for the TTPM is 52 hours plus the additional towing time. Downtime is provided in hours as it is not suitable to normalise for generated power.

4.9.3. Total cost

The total cost of the operation is based on the fuel and charter cost of the vessels. Charter rates of the vessel are calculated by the inhouse Royal IHC tool and the fuel rates are based on the figures provided in table 4.4. The total cost is, for a fair comparison, also normalised to the MWh generated by the FOWTs that underwent a replacement. Unspecified cost in this report are based on the reference fuel MGO.

5

Vessel parameterisation

5.1. Introduction

This chapter provides the answer to the following sub-question:

How can the generalised concept designs of the support vessels be presented in a parametric manner?

From the literature study it became clear that there are currently five different vessel types utilised for major component replacement operations. Each vessel type has its own specific operational profiles and power demands. This power demand translates directly to the fuel consumption which provides the available power. The power demand depends on ship specific parameters which have to be determined. First, it is explained why parameterisation has to be applied. Secondly, the parameterisation study for the different ship models is explained and supported. Lastly, the use of resistance approximation of the Holtrop and Mennen method is discussed.

5.2. Parameterisation

Parameterisation allows the vessels to be transformed into datasets which can be used in the calculation model. This avoids designing a vessel in great detail, which would make it more complex if alterations to scale are required. The dataset will also include correlations between different parameters. For example, the length or the breadth of a vessel in the dataset should be in accordance with the common length-over-breadth-ratio for the considered vessel type. To achieve a viable dataset for each vessel type, parameterisation is partly based on a vessel database derived from the Clarksons fleet register [12].

5.3. Heavy lift vessel

The HLVs are available in two different vessel layouts. One can be described as a large self-propelled semi-submersible barge. These barge-like HLVs are often multi-hull vessels, meaning that they posses multiple floaters. The other setup is the mono-hull vessel, which better represents the more conventional vessel shape and only has one floating body. Differences between the two types of vessels are clearly visible in figure 5.1 and 5.2. Both types can be equipped with one or two heavy duty offshore cranes which are used for hoisting heavy components [67]. There is also the jack-up HLV, which is commonly used in the offshore wind industry. This vessel raises itself from the water, with large "legs". However, it is thought that the water depth in the FOWT market is too great to use this technique and it is therefore not considered in this report [31].
The largest challenge for HLVs in the FOWT or even the fixed offshore WT market is the required lifting height [7]. The last 20 years the hub height has risen by almost 60%, with the potential to become over 150 m for the large 15 MW FOWTs [66]. The model used in this report includes the 15 MW turbine with a hub height of 135 m, which results in a required lifting height of approximately 152 m. Substantiation for the 152 m lifting height can be found in appendix I. This required lifting height results in a lack of vessels which can be used for the parameterisation. Currently, there is only one confirmed mono-hull HLV

which has the potential to maintain the FOWTs in this report. This is the Les Alizés from the Belgian company Jan de Nul. Hence, only this vessel will be included as HLV in this study.

Figure 5.1: A multi-hull crane vessel [24].

Figure 5.2: A mono-hull crane vessel [54].

5.3.1. Les Alizés

The Les Alizés is built for the decommissioning of large offshore oil and gas structures and the installation of fixed offshore WT farms. At the moment its final construction works are taking place with the expected delivery of the vessel in the second half of 2022. The vessel has one main crane of which the auxiliary hook can lift 167 m above deck and has a maximum lifting capacity of 1500 t. This does exceed the earlier mentioned lifting requirements, making it a suitable vessel for FOWT major component replacement. The deck area of the vessel is 9300 m^2, which is very well suited for installation purposes, but relatively extreme for O&M purposes. The deck is assumed to use the full width of the vessel (52 m) and thus be $\pm$ 179 m long. This provides the vessel with a carrying capacity of 60 direct generators, 240 geared generators, 350 gearboxes or 24 blades without overhang.

Next to the deck area information, also the power delivered to all the propellers (P_D) is provided in the specification sheet, which can be found in appendix J. This is due to fact that it depends on the non-dimensional power coefficient (C_D), which in turn depends on variables as displacement, fouling of the hull and sea state. This being said, the assumption remains that c_2 is constant as incorporating these variables requires additional information, which is not provided.

$$P_D = c_2 \cdot V_s^3 \quad \Rightarrow \quad c_2 = \frac{P_D}{V_s^3} \tag{5.1}$$

With the constant c_2 known, the P_D can be calculated for different sailing speeds. These outcomes can in turn be used for the calculations of the P_B according to equation 5.2 [36]. In this equation the power to the propellers is divided by the transmission efficiency (η_{TRM}). The efficiency step is used to describe the energy lost in the transmission from the delivered engine power (P_B) to the power on the propellers (P_D). This energy is lost due to misalignment of bearings or heat generated by friction. For conventional vessels this covers the shaft efficiency and gearbox efficiency. However, the Les Alizés has a diesel-electric propulsion system. In this setup the engines power a generator, which in turn generates electrical energy. This energy is transmitted to an electric motor which powers the propeller. This setup excludes gearbox efficiency as none are in place. Yet, this does lead to other efficiency steps as provided in equation 5.3. This equation incorporates the efficiency steps form engine to generator (η_{gen}), the distributive network (η_{distr}), the transformer (η_{trans}), the power converter (η_{conv}) and the electric motor (η_{em}). Including these values, in accordance with Wärtsilä's provided figures [49], leaves the η_{TRM} to be approximately 94%.

$$P_B = \frac{P_D}{\eta_{TRM}} \tag{5.2}$$

$$\eta_{TRM} = \eta_{gen} \cdot \eta_{distr} \cdot \eta_{trans} \cdot \eta_{conv} \cdot \eta_{em} \tag{5.3}$$

Bunker capacity of Lés Alizés is not publicly available. Therefore, an assumption has to be made based on a similar vessel. A vessel that is comparable to the Lés Alizés is the DEME owned vessel Orion which has a total of 2000 m^3 bunker capacity [12]. After a correction for the size difference the bunker capacity is assumed to be 2300 m^3.

5.4. Platform supply vessel

The PSV is a type of vessel that is used to feed offshore installations with materials and wet or dry bulk cargo. The materials can be stored on deck, while bulk cargo can be stored in designated tanks below deck. The vessel does not posses crane capabilities and therefore materials can only be loaded and unloaded by external cranes. In the HLM strategy, where PSVs are used, the vessel(s) ”feed” the HLV the necessary components for replacement. While being unloaded the PSV makes use of its DP capabilities in order to stay in the same place, allowing safe cargo handling operations [67].

5.4.1. Generalised parameters

In contrast to the HLVs, the PSVs are build in larger quantities allowing parameterisation. Since the main job of the PSV is to retrieve components from the O&M port and bring them to the HLV in the field, the loading capacity is classified as a key parameter. For the same reason the transport/transit speed is also deemed an important parameter. Additionally, it is vital to know how many bow thrusters are fitted onto the vessel and if a bulb is in place. The later two are important for vessel resistance calculations, which will be done with the Holtrop and Mennen method [26], as described in section 5.6. For this reason additional variables have to be derived to determine the required engine brake power. The carrying capacity dictates the deck area required for transporting the desired amount of components. With the assumptions made in section 4.3.1, regarding the component weight, it can be found what the minimum required deck area needs to be, based on the general deck strength. A PSV database generated from the Clarksons vessel database, was used to determine the most common deck strength [12]. From the 1022 vessels, with a specified deck strength, more than 57% indicated to have a deck strength of 5 t/m^3. This is followed by a deck strength of 10 t/m^3 at a tight 17%. This information, together with the information found in section 4.3.1, provides the following required deck areas.

- Deck area direct generator : 11.03 m x 11.03 m
- Deck area indirect generator : 7.42 m x 7.42 m
- Deck area gearbox : 7.42 m x 7.42 m
- Deck area blade : 117 m x 5.20 m

After the required deck area is determined, other parameters can be derived from it. The length between perpendiculars (L), breadth (B) and draught (T) of the vessel are found with PSV Clarksons database and MATLAB curve fitting tool [12]. Graphs are provided in appendix K, with the outcomes presented below.

Components other than blades:

$$
\begin{aligned}
L &= 0.0426 \cdot A_{deck} + 39.54 \\
B &= 0.009048 \cdot A_{deck} + 10.32 \\
T &= 0.3752 \cdot B + 0.7021
\end{aligned}
\tag{5.4}
$$

A special case are the blades that have to be transported, as they set a hard demand for the minimum length of the vessel, a so called blade carrier. The assumption is made that the deck length of a representative PSV is 75% of the total length of the vessel, leading to a vessel length of 156 m. With a correlation between the length and breadth of the vessel, the breadth is approximately 33 m. This breadth is deducted by 10% to incorporate the boarding of the vessel, leading to a deck breadth of roughly 30 m. Hence five blades can be stored on deck adjacent to one another. The assumption is made that three blades can be stacked upon each other with the use of stacking frames. This has been done before in the industry, as for instance on the vessel the MV BoldWind of Vestas. This makes the blade carrier PSV carry up to 15 blades in one trip. The draught of the PSV blade carrier is determined in the same way as for the PSVs, which are not intended for blade transport.

Blades:

$$\begin{aligned} L &= 117 \cdot (100/75) = 156m \\ B &= 0.95 \cdot (0.1909 \cdot L + 3.447) = \pm 32m \\ T &= 0.3752 \cdot B + 0.7021 = \pm 12m \end{aligned} \tag{5.5}$$

The variables that are derived can in turn be used to determine the final parameters necessary for the Holtrop and Mennen resistance approximation, as discussed in section 5.6.

The analysis of the considered dataset does not show a clear correlation between different vessel parameters and bunker capacity. This is caused by the fact that PSVs often also carry fuel tanks as cargo, which seem to be included in the bunker capacity figures. To still get a good approximation of the bunker capacity it is decided that the bunker capacity scales equal the bunker capacity of the AHTS vessels, as there is not a large difference between the two vessels. The equation used for parameterisation is based on the breadth (B) of the vessel as shown in equation 5.8. The dimensions of the blade carrier are well beyond the normal range of PSVs. Therefore, bunker capacity is estimated on the comparable vessel, the Rolldock owned BigRoll Biscay, which has a bunker capacity of 2100 m^3 [12]. The assumption is made that the bunker capacity is equal for the blade carrier.

The minimum and maximum parameters of the PSVs are shown in table 5.1.

Table 5.1: Minimum and maximum parameters for the PSV and blade carrier.

Type	Component	min. carrying capacity (#)	max. carrying capacity (#)	min. sailing speed (km/h)	max. sailing speed (km/h)
PSV	GB gen. / gearbox	2	24	10	28
PSV	DD gen.	1	11	10	28
Blade carrier	Blade	15	15	10	28

5.5. (Assisting) Anchor handling tug supply

The AHTS vessel is a vessel type that is designed to carry out three distinct tasks. The first task is the task of anchor handling vessel. This means that it is capable of setting and retrieving anchors for offshore structures. The second task is the task of tug vessel, allowing it to wet-tow offshore structures from and to site. The final task overlaps with the main task of the PSV, as it is able to supply materials and wet and dry bulk cargo to offshore structures [67].

5.5.1. Generalised parameters

In the FOWT industry the supply capabilities will be less relevant. Moreover, during the O&M phase of a FOWT farm the anchors are in place and are assumed to not be taken out when disconnecting the FOWT, leaving the towing of the FOWTs as main parameter for the vessel type. The towing of the FOWTs requires a bollard pull (BP), i.e. towing strength, of roughly 120 t for the SPAR type FOWT and 220 t for the semi-submersible FOWT, which are both described in appendix A. Further calculations regarding the minimum BP can be found in appendix L. With the BP as main parameter, other variables can be derived from it to approximate the hull resistance and estimate the required P_B. Hull resistance approximations for this vessel can also be done with the Holtrop and Mennen method, described in section 5.6. Therefore, also the number of bow thrusters has to be determined together with the presence of bulb.

Length (L), breadth (B) and draught (T) of the AHTS vessels is estimated with the use of an AHTS Clarksons database and MATLAB. Supporting graphs are provided in appendix M, with the outcomes presented below.

$$\begin{aligned} L &= 0.165 \cdot BP + 28.4 \\ B &= 0.03738 \cdot BP + 9.673 \\ T &= 0.01695 \cdot BP + 3.346 \end{aligned} \tag{5.6}$$

The required P_{Btow} during towing operations differs vastly from the P_B required during transit conditions. The Holtrop Mennen approximation is not intended for calculating the resistance during towing. P_{Btow} is therefore determined from the correlation with BP, derived from the Clarksons database. This resulted into the following correlation (graph in appendix M).

$$P_{Btow} = 58.97 \cdot BP_{max} - 77.04 \tag{5.7}$$

The bunker capacity estimation is also based on the AHTS database. It is decided that it will not scale on the BP of the vessel as it also utilised for the PSV. The equation used for the bunker capacity is shown below.

$$BC = 71.17 \cdot L - 2292 \tag{5.8}$$

The minimum and maximum parameters of the AHTS vessels are shown in table 5.2.

Table 5.2: Minimum and maximum parameters for the AHTS vessels.

Type	Floater type	min. BP (t)	max. BP (t)	min. sailing speed (km/h)	max. sailing speed (km/h)
AHTS	SPAR	120	400	10	28
AHTS	Semi-submersible	220	400	10	28
Assisting AHTS	DD gen	120	120	10	28

5.6. Holtrop and Mennen

The Holtrop and Mennen approximation is used to determine the calm water resistance for the PSV and (assisting) AHTS vessel [26]. This method was developed in 1978 and refined in 1982, which has an empirical basis. It should be noted that an important boundary in this method is that the vessel does not include planning. However, this does not apply for the PSV nor the (assisting) AHTS vessel.

The resistance of a ship can be divided into six subdivisions, as shown in equation 5.9. It consists of the frictional resistance (R_F) multiplied by the form factor (1 + k_1), added by the resistance of the appendage (R_{APP}), the wave making/breaking resistance (R_W), the additional resistance of bulbous bow near the water surface (R_B), the additional pressure resistance of the immersed transom stern (R_{TR}) and the model-ship correlations resistance (R_A).

$$R_{tot} = R_F(1 + k_1) + R_{APP} + R_W + R_B + R_{TR} + R_A \tag{5.9}$$

5.6.1. Frictional resistance

The frictional resistance is calculated according to the ITTC-1957 friction formula, provided below.

$$R_F = \left(\frac{1}{2}\right) \cdot \rho_{sw} \cdot V_s^2 \cdot C_F \cdot S \tag{5.10}$$

In this equation the ship speed is labelled as V_s and the seawater density as ρ_{sw}, which is assumed to be 1025 kg/m^3. The friction resistance coefficient (C_F) in the equation depends on the Reynolds number (Re) as shown in equation 5.11 [61]. The Reynolds number in its turn depends on the ships speed length of the waterline (L_{wl}) and the ships speed and kinematic viscosity (υ). The L_{wl} is assumed to be equal to L. The kinematic viscosity is 1.1832 mm^2/s at 15 °C according to the ITTC recommended procedures [29]. The expression for the Reynolds number is shown in equation 5.12 [36].

$$C_F = \frac{0.075}{(log_{10} \cdot Re - 2)^2} \tag{5.11}$$

$$Re = \frac{V_s \cdot L_{wl}}{\upsilon} \tag{5.12}$$

The other variable that has to be determined is the wetted area of the hull (S). The wetted area depends on the unknowns; block coefficient (C$_B$), midship section coefficient (C$_M$), waterplane area coefficient (C$_{WP}$) and transverse bulb area (A$_{BT}$). The latter will be set to zero as both vessel types do not posses a bulb. C$_B$ is the ratio between the underwater volume, L, B and T [67]. However, the underwater volume can not be determined with the already known variables. Hence, the empirical approximation formula, shown in equation 5.13, is applied. For modern ships C is assumed to be 1.06 [56]. The formula using the Froude number is shown in equation 5.14 [36].
C$_{WP}$ is the ratio between the waterline area, L and T [67]. The waterline area is an unknown. Therefore, an empirical approximation formula is applied to determine C$_{WP}$, shown in equation 5.15. Note that this equation assumes an average stern section [56].
C$_M$ is the midship section coefficient and is the ratio between the midship section area and B and T. The midship section area is unknown and estimated with the use of table 5.3 [56]. This table does assume a rise of floor, which is unique for vessel types as tugs and fishing vessels. The assumption is made that the PSVs also have a rise of floor, since these vessels often also posses towing capabilities, albeit to a lesser extent.

$$C_B = C - 1.68 \cdot Fr \tag{5.13}$$

$$Fr = \frac{V_s}{\sqrt{g \cdot L}} \tag{5.14}$$

$$C_{WP} = \frac{1 + 2 \cdot C_B}{3} \tag{5.15}$$

Table 5.3: Recommendations for CM of ships with rise of floor.

C$_B$	C$_M$
0.75	0.987
0.70	0.984
0.65	0.980
0.60	0.976
0.55	0.960

5.6.2. Form factor

The form factor used in the Holtrop Mennen approximation is provided in the equation below.

$$1 + k_1 = c_{13} \cdot \left(0.93 + c_{12} \cdot \left(\frac{B}{L_R}\right)^{0.92497} \cdot (0.95 - C_P)^{-0.521448} \cdot (1 - C_P + 0.0225 \cdot lcb)^{0.6909}\right) \tag{5.16}$$

The variable c$_{13}$ can be calculated with the assumption that all vessels have a normal section shape. c$_{12}$ can be calculated with the known variables. The longitudinal centre of buoyancy (lcb) has to be estimated as it is based on the underwater volume of the vessel. Schneekluth does provide an approximation to determine the lcb, but this is based on Japanese ships and could potentially differ from ships built elsewhere [56]. A study from Kondratenko on Artic factors on the PSV and AHTS vessels includes a database of 115 vessels, excluding sister vessels. This database indicates that the C$_B$ ranges from 0.58 up to 0.78 [37]. Taking the average between the two leads to a C$_B$ of 0.68. When this C$_B$ is plotted against the optimal lcb position, it is found that the lcb lays approximately at 1.5% L aft of the midship. The plot is visualised in figure 5.3.

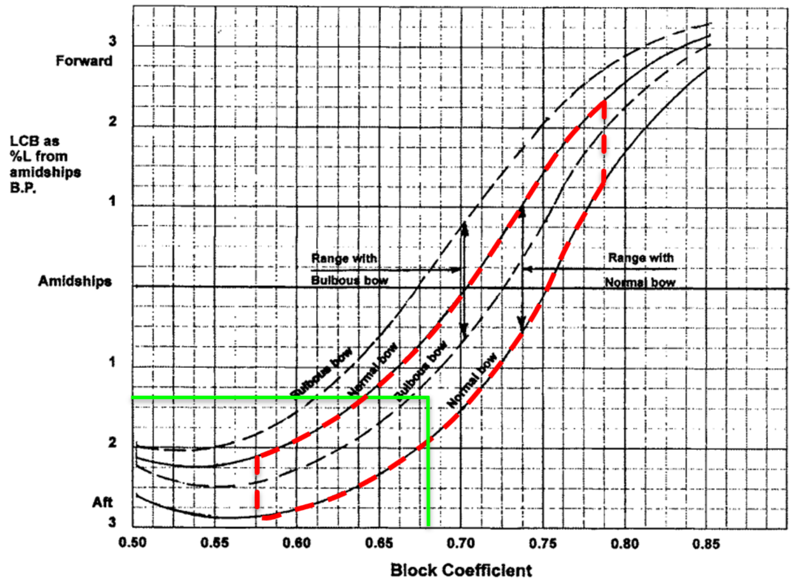

Figure 5.3: The assumed lcb position for the PSV and AHTS vessels [70].

The last unknown is the prismatic coefficient (C_P), which reflects the ratio of the volume of displacement at that draft to the volume of a prism having the same length as the ship and the same cross-sectional area as the ship's midships area. C_P can be calculated with equation 5.17. With all the known variables at this point the form-factor L_R can be calculated.

$$C_P = \frac{C_B}{C_M} \tag{5.17}$$

5.6.3. Resistance of the appendage

The appendage resistance is calculated with equation 5.18.

$$R_{APP} = \frac{1}{2} \cdot \rho_{sw} \cdot V_s^2 \cdot S_{APP} \cdot (1 + k_2)_{eq} \cdot C_F \tag{5.18}$$

Most of the variables necessary to derive R_{APP} were already found in previous calculations. The unknown variables which remain are $(1+k_2)_{eq}$ and the wetted area of the appendages S_{APP}. The $1+k_2$ values are provided for different appendages in the Holtrop Mennen paper. However, the appendages mentioned are not likely to be placed on a PSV or AHTS vessel and will therefore not be included in further calculations. But, as mentioned before, the bow thrusters are included in the resistance calculation. The bow thrusters, or rather bow thruster openings, create additional resistance, which has to be added to R_{APP}. The additional resistance can be calculated as follows.

$$R_{bt} = \rho_{sw} \cdot V_s^2 \cdot \pi \cdot d^2 \cdot C_{BTO} \tag{5.19}$$

The function $\pi \cdot d^2$ describes the circumference of the bow thruster opening, with d being the tunnel diameter. The variable C_{BTO} should be between 0.003 and 0.012. Due to the lack of a bulbous bow it is noted that a higher value should be used. From a conservative perspective it is decided that the used value in the model is 0.012.

5.6.4. Wave resistance

The wave resistance can be approximated with the equation below.

$$R_W = c_1 \cdot c_2 \cdot c_5 \cdot \Delta \cdot g \cdot e^{m_1 \cdot F_n + m_2 \cdot cos(\lambda \cdot F_n^{-2})} \tag{5.20}$$

Almost all variables in this equation can be solved with the findings up to this point. The exception is the displacement (Δ). The displacement is the submerged volume of the complete vessel and is calculated with an equation with the known variables, as shown below.

$$\Delta = L \cdot B \cdot T \cdot C_B \tag{5.21}$$

It should be noted that the variables regarding the bulbous bow are set to zero as both vessel types are assumed to not have such a bow. Hence, the bulbous bow near the surface resistance is also set to zero.

5.6.5. Immersed transom stern resistance

Additional resistance is encountered when the stern is submerged during sailing and is calculated with the following equation.

$$R_{TR} = \frac{1}{2} \cdot \rho_{sw} \cdot V_s^2 \cdot A_T \cdot c_6 \tag{5.22}$$

The seawater density and ships speed are known. But the transom area (A_T) is unknown and is also required to calculate c_6. This transom area can be approximated with a correlation to Fr. It is assumed that Fr will not exceed 0.5 and the conservative A_T value of 10% of T times B is taken.

5.6.6. Model-ship correlations resistance

The model-ship correlations resistance describes the effect of the hull roughness and the still air resistance and is calculated according to equation 5.23.

$$R_A = \frac{1}{2} \cdot \rho_{sw} \cdot V_s^2 \cdot S \cdot C_A \tag{5.23}$$

All variables are either known or can be calculated according to the Holtrop Mennen paper, with the known variables.

5.7. Closing remarks

The aim of this chapter is to provide more information on the different parameterisations performed. Parameterisation allows for estimation on different vessel parameters, while avoiding the burden of designing a vessel in great detail. The HLV is an exception as there are currently not enough crane vessels to perform a well founded parameterisation. To still implement the HLV into the model, it is decided that the floating wind installation vessel the Les Alizés will be included. The PSV and AHTS vessel are parameterised based on different databases and parameters. The deck capacity (carrying capacity) is deemed to be the variable of which other parameters are derived. The AHTS vessel on the other hand is based on the variable bollard pull as it has to tow the FOWTs from and to the field. The parameters of and assumptions on the different vessel types are then used to make an approximate power prediction with the Holtrop and Mennen method. It must be noted that the parameterisation method is a practical method, which could provide good estimations. However, information derived from this method remains an approximation, whereas detailed vessel design could provide a better estimation. Nonetheless, the parameterisation study is deemed sufficiently accurate to use in the calculation model.

6

Model verification

6.1. Introduction

This chapter provides the answer to the following sub-question:

> *How can the model that is used for finding the most effective solution maintenance strategies be verified?*

The outcomes of the model have to be placed into perspective to determine the quality of the generated data. This chapter covers the possibilities to interpret this quality. First, the possibilities on validation and verification are provided. Thereafter, a case study is performed for the newest FOWT farm ”Hywind Tampen”. This case study will then be used for a sensitivity study to test the robustness of the model and identify possible errors. The chapter is closed with a summary on the outcomes of this chapter.

6.2. Validation and verification

The model generates output based on a variety of different peer reviewed literature sources and several assumptions discussed throughout this report. Despite this basis, it does not necessarily lead to a correct model, as data or program errors could slip into the model during the development. Therefore, the model preferably has to be validated or at least verified. The possibilities for validation and verification for this model will be discussed.

6.2.1. Validation

To validate the model it is necessary to compare the outcomes to existing real life scenarios. During these scenarios measurements have to be performed and data has to be collected. Even if the data from the model matches with data gathered during the scenario, interest lays predominantly in future scenarios. These scenarios can not be validated fully as there is currently no existing real life scenario to compare the data to. A certain level of confidence in the model can still be achieved when a large variety of existing scenarios is available [16]. However, for novel industries like the FOWT market there is no large range of scenarios, let alone data, available. Therefore, the model can not be validated appropriately at this point.

6.2.2. Verification

An alternative to validation is verification, where the model can be tested to other models. This is called the code-to-code comparison or intercomparison. To successfully perform a code-to-code comparison, it is necessary to use the same input data and know what assumptions are made in the model [16]. Unfortunately, this is unclear for all literature reports found that cover GHG emissions. For example, the paper of N. Yildiz focuses specifically on the emission during the O&M phase of FOWTs. In this paper a 2 MW FOWT undergoes several different maintenance scenarios, ranging from a simple inspection to full blade replacements [72]. However, the majority of aspects of the scenarios remains unclear. It is unknown how long the vessels are in operations and what distinguishes an active inspection from actual repair. Another example would be the paper from J.K. Kaldellis, where data regarding fuel consumption, operational time and cost are derived from not attached 'personal communication' [33]. This makes that code-to-code comparison cannot be performed, unless all the authors cooperate and share their data. Another approach to verify the model is by running different cases and vary input parameters to see if the model reacts as expected. This could be considered as a stress test. Additionally, the values that the model generates have to be checked on reasonableness. Initial steps in this check can be performed by experience and common sense. If this is not possible, the values should be compared to literature sources to see if they are in the same ball park [9]. The test on reasonableness is conducted on the operational time of the vessels and the Holtrop and Mennen resistance approximation. The operational time of the vessels is compared for different samples of all fleet configurations to hand calculations. The Holtrop and Mennen script is tested on the numerical example that is provided in the paper. It is decided that the model will undergo a sensitivity analysis to test the robustness of model. This is considered a stress test and outcomes will be analysed. Moreover, it can be used for recommendation on where the model might need improvement [47].

6.3. Case study

The sensitivity study will be based on a case study of the newest FOWT farm Hywind Tampen. It is the first fully commercial FOWT farm and consists of eleven 8 MW turbines on SPAR type floaters. However, for this case the assumption is made that the FOWTs will be 15MW turbines as this is more in line with the report. The case study will be treated in the same way as the model goes through the different modules described in section 4.2. Note that for this scenario also the weather module will be included.

6.3.1. Weather module

The weather data is generated by and derived from the Copernicus platform, which provides freely available climate data and functions [13]. The variables derived from Copernicus are the u and v component of the wind, together with the significant wind wave height. The data is derived for the Hywind Tampen location, which is 61°20 N and 2°42 E [57]. First the hypotenuse is determined from the u and v wind components, to get the absolute wind speed at the Hywind Tampen location. This wind speed can in turn be used to approximate the wind-wave relation for that specific location, as shown in appendix F. The absolute wind speed will also be used to determine the capacity factor, for which the power curve has to be available.
The average wind speed in the generated weather is 7.9 m/s and the significant wind wave height (Hs) is 2.4 m. Seastates, another publicly available weather database, estimates the average wind speed in this location at 8.6 m/s and the Hs at 2.8 m [1]. This could be an indication that the model slightly underestimates the wind speed and Hs. However, the data from Seastates is based on at least 20 years of weather observations and is not based on ERA5 data.
The capacity factor for the FOWT, based on the generated weather timeline, is 0.49, which results in 17810 GWh generated power. Note that the capacity factor of the FOWT is considered to be representative for the entire farm.

6.3.2. Failure module

The generated timeline can now also be used to create a failure data set, which will be used to activate the different fleet configurations. The failure rates used in this case are the same as shown in table 4.3 and lead to the failure data set as shown in appendix N.
The number of failures seems to be relatively high, with an average of 2.4 major component replacements per year. The data set does provide more information than just the number of failures. It also shows at which hour the failure occurs, which will be implemented as start time for the breakdown maintenance tasks. Another important detail to point out in the failure data is the type of component which has to be replaced. Especially for the HLM strategy it is important to know which component fails, as not all PSVs can carry all types of components. Also, the number ID of the FOWT is provided, but is currently not used in further calculations.
In addition to these maintenance requests a preventive maintenance task could be added for the replacement of the blades. However, blade lifetime is currently estimated to be approximately 25 years [6]. Thus a blade replacement campaign is not implemented in the model.

6.3.3. Support vessel strategy module

For the purpose of the sensitivity analysis it is decided that only HLM configuration 1 and TTPM configuration 4 are considered. Both configurations are the most basic within their strategy and do provide the basis for all other configurations. The relative simplicity of the configurations also allows for better error checking and parameter variations.

Output variables

The breakdown maintenance performed by configuration 1 results in an average FOWT downtime of 110.9 h considering all breakdown replacements performed. This clearly indicates that the FOWT downtime can be strongly influenced by the weather at the site, as the minimum FOWT downtime would be 62.6 h. The finding that the FOWT downtime increased by almost 80% does not necessarily reflect the actual downtime at the location of the case study, as this is based on just one wind/wave run. Another aspect that is influenced by the environmental challenges is the operational time of the vessel. Before a vessel can start an operation, it is checked if the operational limits, provided in table 4.2, are not exceeded. If this is the case the model ”waits” one simulation hour and than checks again, until a suitable weather window is found. This means that the vessel has to wait in port or at the field until the weather window is found and this waiting time is on average 46.7 h per operation. This does automatically translate to a higher minimum cost of 3.812 €/MWh due to the prolonged charter time. Note that the cost is based on the 60 failures in 25 years time considering the complete farm. The minimum energy demand is estimated to be 3.715 kWh/MWh for the complete farm, which is on average 0.681 kWh/MWh per failure per FOWT. Compared to the numbers found earlier in this report this is relatively high. The increase can be explained by the fact that the HLV also has to wait in field for a weather window at a higher energy demand profile.

Configuration 4 seems to be off in terms of FOWT downtime, as the average downtime is estimated to be 1477 h. This would imply that on average the FOWT cannot be serviced for roughly two months. However, it must be noted that this number is a direct consequence of a model decision, regarding the weather timeline. The weather timeline is created with the Markov chain model, as explained in section 4.4.1, but based on the entire year. Seasonal changes are not included, resulting in a large deviation from one hour to the other. Added to this is the relatively extensive period where operational limits are in place, due to the additional towing and hook on/off operations. This being said, it still shows something interesting. As the model uses the same timeline for the HLM configuration, it shows that the TTPM configuration is more prone to weather influences than the HLM configuration, due to its extended operational duration. Outcomes regarding cost and energy demand are almost twice the cost of the HLM configuration. However, it is likely that these figures are significantly lower in practice.

6.4. Sensitivity analysis

The sensitivity study will be performed on different aspects of the model. First, the weather module will be discussed, based on the findings from the case study. Other variables that are highlighted to be suitable for a sensitivity study are the number of activities that are performed and technical parameters [47]. Therefore, it is decided that the input variables failure rate and repair time are varied. Moreover, the energy demand of the port idle and DP profiles will be varied to see how the model reacts to this. Note that these variations are performed without weather timeline, apart from the failure rate.

Weather module

In essence, there is already a small sensitivity study performed on the model during the case study. It was shown that the time in which operational limits are in place can heavily affect the outcome. Another example that can show the effect is the replacement campaign of the blades. The duration of these blade replacements is estimated to be three times the normal replacement time of 52 h. This results in the necessity of 156 h of consecutive weather timeline per FOWT, where the Hs does not exceed 1.5 m and the wind speed remains below 12 m/s. The weather timeline generated by the model does not provide enough weather windows that agree with these limits, resulting in an unfinished campaign. This shows that the weather model can be used for tasks which either have low operational limits or have a shorter duration. Despite this shortcoming it can still be used to provide useful information on the potential capacity factor in a certain geographical location.

Failure rate

In the case study the number of failures was found to be 60 for the entire farm during its complete lifetime. Hereafter, nine more runs were conducted to determine the variance in number of failures per component. The bandwidth found from the runs is shown in figure 6.1. It shows that the number of generator failures lays between 18 and 32 failures for the complete FOWT farm per lifetime. Moreover, the lower bound for gearboxes is 28 failures with an upper bound of 45 failures. Blade failures did not occur in any of the runs. The outcome does already show that between different runs with the same weather timeline a considerable distribution is present. To see the effect of another failure rate it is decided to use a failure rate of 0.08, which is provided in another paper of J. Caroll [16]. As it is not specified per component it is assumed that the distribution between the components is equal to that of earlier mentioned failure rates. Again, ten runs were performed and also shown in figure 6.1. Note that during these runs the weather timeline is equal to the timeline used for the other runs. It shows that a 68% reduction in failure rate does result in a shift in range for the failures. The total number of failures is now 5 to 16 and 8 to 19 for the generator and gearbox respectively. This is a relative decrease of roughly 70% in the lower bound and 50 to 60% in the upper bound, demonstrating to respond more or less in a linear manner.

Figure 6.1: The different amount of failures for different failure rates.

Repair time

In this report it is assumed that the repair time is 52 h. For the sensitivity analysis the repair time will be varied between 80% and 120% with a step size of 10%. Repair time is chosen for the sensitivity analysis as it is relatively dominant in the cost calculation, due to the time it occupies. Moreover, it also affects the energy demand for the HLV that performs in field repairs. Downtime will also be affected, but likely in a slighter way. The analysis will be done for configuration 1 and 4, for similar reasons as discussed during the case study.

Configuration 1 seems to react fairly sensitive to the changes in repair time. The largest response is observed for the energy demand which varies between -18.4% and 18.4%. Downtime and cost are both having a lower response with output varying between -16.6% and 16.6% for the downtime and -14.2% and 14.2% for the cost. Findings are shown in figure 6.2.

Configuration 4 demonstrates to be more robust as the observed changes are just a fraction of the findings for configuration 1. The downtime shows not the largest variation of roughly 8% both ways. The cost also is affected by the change but by a mere 6%. Energy demand is the most robust for this analysis with a change of -1% and 1%. These findings are visualised in figure 6.3.

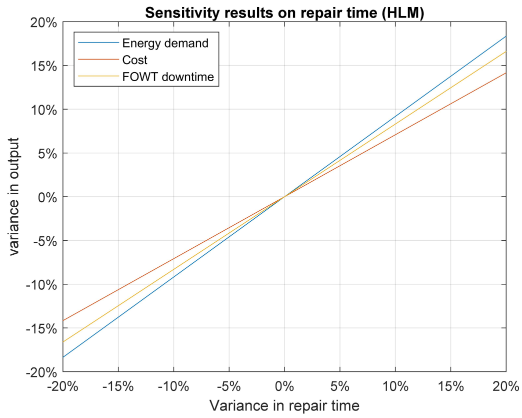

Figure 6.2: Sensitivity results for the HLM configuration.

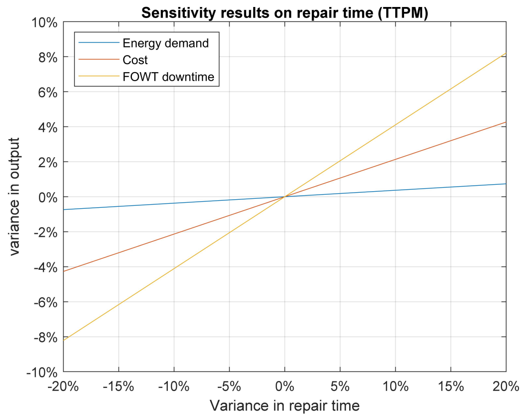

Figure 6.3: Sensitivity results for the TTPM configuration.

Port idle
The port idle energy demand is present for a relatively large portion of the time in configuration 4 and is therefore included in the sensitivity study. Again, a variation will be made between 80% and 120% of the port idle energy demand. Downtime will not be included in this part of the sensitivity analysis as this is not affected by any change in energy demand.
Configuration 1 does nearly not respond to the changes in port idle time, which can be explained by the nature of the strategy. Cost and energy demand vary with a maximum of 0.1%, indicating configuration 1 is very robust on this part.
Configuration 4 demonstrates to be slightly more affected by the changes in port idle time. Energy demand varies with 1.5%, indicating that this configuration is still very robust despite the extended time in port.

Dynamic positioning
It was found in previous analyses in this report that the DP profile has a relatively high energy demand. This could indicate that the model is relatively sensitive to change in the DP energy demands and is therefore included in the sensitivity analysis.
Configuration 1 does indeed react fairly sensitive to changes. The energy demand fluctuates between -18.4% and 18.4%, which is considered a large variation. Cost on the other hand does not demonstrate to be heavily affected by the changes, with a variance of 1.1% both ways.
The analysis on configuration 4 does show that the energy demand is less susceptible to variation in DP energy demand. However, it is still considered to be significant as changes from -15.2% to 15.2% are observed. Cost is still very robust, with a deviation of 2.5% both ways.

6.4.1. Verification based on the sensitivity analysis

The sensitivity analysis is used to test the robustness of the model, but is also used to verify the model. The verification can be performed using the same output found in the sensitivity analysis. First, the failure rate of the components is set to a lower failure rate. The lower failure rate does lead to a lower number of total failures. This shows that the failure module acts in accordance with the expectation, since a lower failure rate leads to less failures considering the complete lifetime. The second parameter that was varied, was the repair time of the FOWTs. It is expected that the energy demand, cost and FOWT downtime drop if the repair time is lowered and rise if the repair time is increased. This is due to the fact that the operational time of the vessel increases or decreases in accordance with the repair time. The same goes for the FOWT downtime. This expectation is met in the sensitivity analysis as shown in figure 6.2 and 6.3. The sensitivity analysis also showed that the lower port idle energy demand has a linear correlation with the cost and energy demand. Again, this is in line with the expectation as the lower energy demand lowers the fuel consumption and thus the cost of the entire operation. Moreover, the lower energy demand in one operational profile lowers the total energy demand considering the complete replacement operation. The same goes for the lower energy demand of the DP profile, where the similar response from the model was observed. The weather module showed to be flawed for operations of extended duration where weather limits are in place and could therefore not be verified.

This is also an argument to first increase the performance of the weather model before it can be used for further analysis purposes.

6.5. Closing remarks

The main purpose of this chapter is to assess the quality of the model and the outcomes. One way to do this is validation against real life data. Unfortunately, validation is not possible as there is currently no public data available that could support the findings of the model. This is inherent to the fact that the FOWT industry is still in its infancy and that there are just a few projects realised. Code-to-code verification, based on literature sources, can also not be performed without the cooperation of other authors, as more insight in assumptions is needed. To still test and verify the model, a case study and sensitivity analysis was performed. The case study showed that the current weather model is too stochastic as it does not take into account the seasonal changes. It can be used for a relatively short operation demand, but does already provide unrealistic outcomes for the TTPM configuration, which has prolonged operational limits in place. The sensitivity analysis demonstrated that the HLM configuration reacts fairly sensitive to changes in repair time and DP power demand. The TTPM configuration is also sensitive to changes in DP energy demand, but shows less reaction to changes in repair time compared to the HLM configuration. Both configurations showed to be very robust for changes in port idle energy demand. The findings from the sensitivity analysis, together with the verification steps, show that the model is a reliable tool to compare different strategies to each other and potential new concepts.

7 Heavy lift maintenance strategies

7.1. Introduction

This chapter provides the answer to the following sub-question:

> *What is the most effective solution to improve the sustainability of major component replacements in a floating offshore wind farm, considering utilisation and parametric design of support vessels used in the heavy lift maintenance strategy?*

In this chapter a detailed view on the different HLM configurations is provided, which are listed in section 4.6. First, the analysis parameters are discussed, which will be used for comparison of the selected configurations. Secondly, the configurations are compared on breakdown maintenance for different FOWT farms. This comparison ends with the overview of the impact of the sailing speed and the potential correlations in analysis parameters. Thirdly, the several preventive maintenance tasks of the same FOWT farms are used for the comparison of the HLM configurations. For both the breakdown and the preventive maintenance tasks a distinction is made between the different components. The impact of alternative fuel selection is also considered, next to the different configurations. Lastly, a brief overview is provided on the findings of this chapter.

7.2. Analysis parameters

To compare the different strategies certain parameters must be chosen. HLM breakdown strategies can be analysed on three different parameters. The first parameter is the FOWT downtime, i.e. the time before the FOWT is repaired and operational again. The second parameter is the total cost of the operation and the third is the total GHG emission, caused by the fuel consumption. The GHG emission can be reduced by choosing an alternative fuel, shown in table 4.4. Coming back to equation 4.6, it shows that the energy demand dictates the mass of GHG emission, if the HLV and per are factorised per fuel. Therefore the energy demand will be taken as output parameter on which the analysis is based. The cost can also be factorised, but this has to be done for each configuration specifically. Cost in this analysis will be based on the reference fuel MGO, which allows for comparison of the different strategies.

FOWT downtime will not be considered as analysis parameter for the preventive maintenance campaigns, under the assumption that the FOWT will only shutdown when the HLV closes in on DP. Thus, resulting in an equal FOWT downtime for all configurations and farms which are analysed. The size of potential breakdown campaigns is something that is decided on by a FOWT farm operator. As this is seen as a management decision it is considered outside the scope of this research.

The output parameters are in €/MWh for the cost and kWh/MWh for the energy demand, where MWh is the energy produced by the number of FOWTs that undergo maintenance. The assumption is made that every FOWT has an expected operational lifetime of 25 years, a capacity factor of 50% and has a rated power of 15MW. FOWT downtime is provided in total hours, as it is not suitable for normalisation and only considered for one FOWT at the time.

7.3. Breakdown maintenance

During the breakdown maintenance there is just one FOWT that requires one component to be replaced. Therefore, not all HLM fleet configurations will be considered for this type of maintenance. Configuration 1 utilises a HLV with the carrying capacity to transport a single component for replacement. In configuration 2 the carrying capacity is provided by the PSV. The HLV in configuration 2 is only used as a crane vessel and has no carrying capacity of its own. Configuration 3 will not be considered, as it is illogical to sail two PSVs for one component. The parameter that is varied during this analysis is the sailing speed of the vessels that are involved.

7.3.1. Downtime

All components

The downtime of FOWTs is equal for all components considering a specific configuration. This is due to the fact that all components undergo the same procedure, which requires an equal amount of time. First, the component is loaded and then transported to the site where it is used for the replacement. Yet, the FOWT downtime still slightly differs between the different configurations. Configuration 1 has a minimum FOWT downtime of 57.4 h, 59.0 h and 61.0 h for farm A, B and C respectively. Configuration 2 on the other hand has a minimum FOWT downtime of 57.4 h, 58.8 h and 60.6 h for farm A, B and C respectively. This minor decrease in FOWT downtime between the configurations is the result of performing processes parallel. The component can be loaded by the PSV, while the slower HLV starts to transit to the field right away. The faster PSV can then catch up with the HLV. Although there is a benefit in terms of FOWT downtime, it is negligible considering the entire operation. Generally speaking the FOWT downtime decreases when sailing speed increases.

7.3.2. Energy demand

Blade

The replacement of a blade is an operation with a relatively high energy demand for configuration 2, even when sailing at the slowest speed. The lowest energy demand is 0.815 kWh/MWh for farm A, which increases up to 0.834 kWh/MWh for farm B and 0.858 kWh/MWh for farm C. Configuration 1 needs 49.8% less energy to replace the blade. This significant difference is the result of two assumptions. The first assumption is that the HLV used in both configurations is the same. The additional vessel, which is of considerable size, will always increase the energy demand. This also leads to the second assumption, that the blades are always brought to the site with a relatively large vessel as no overhang of the blades is permitted. For both configurations it was found that the energy demand is lowest when the sailing speed is brought down to a minimum.

Direct drive generator

The energy demand for DD generator replacement does not change for configuration 1 compared to the blade replacement as the procedure and vessel remain the same. This is contrary to configuration 2 where the blade carrier can now be switched out for a much smaller PSV, dedicated to transport one DD generator at the time. The smaller PSV has a noticeable effect and drops the energy demand to 0.492, 0.504 and 0.519 kWh/MWh for farm A, B and C respectively. Yet, this is still 21.5% above the energy demand of configuration 1. Again, the lowest energy demands are obtained at the lowest sailing speeds.

Gearbox and gearbox-generator

The PSV that is used for transporting the gearbox and/or GB generator is the smallest vessel in the model with a deck area of 111 m^2, which is slightly smaller compared to the smallest PSV that transports DD generators. This minor change in size also comes back at the lowest energy demand for the replacement at 0.491, 0.503 and 0.518 kWh/MWh for farm A, B and C respectively. The energy demand for farm B seems equal to the DD drive case, but this is due to rounding off. Configuration 1 still has the same energy demand as for the other components.

7.3.3. Cost

Blade

The cost of replacing a blade is 0.285 €/MWh for the wind farm closest to shore and increases to 0.301 €/MWh for wind farm B and 0.321 €/MWh for wind farm C for configuration 1. Configuration 2 is on average 0.025 €/MWh more expensive, which comes down to a total of just above 41 k€ per replacement. This is a significant disadvantage when compared to the total cost of almost 450 k€. This does indicate that the additional cost of the blade carrier does not compensate for the reduction in loading time of the HLV. Another observation that can be made is that the cost decreases as sailing speed increases. This sounds counter-intuitive, but can be explained by the charter rate of the vessel. The charter cost is calculated by the hours the vessel is operational. Thus, sailing faster results in less operational time, which reduces the total cost despite the additional cost of the extra fuel that is consumed. It must be noted that this is not a realistic scenario, indicating that the cost model is less suitable for its current use. However, it does still provide a reasonable assumption to compare different configurations.

Direct drive generator

Configuration 2 is now the cheapest option for the replacement of a DD generator. The cost of configuration 1 remains equal to the blade case, but configuration 2 drops to 0.264, 0.281 and 0.303 €/MWh for farm A, B and C respectively. This indicates that the save from the HLV loading and unloading time is worth the benefit. The HLV has an estimated charter rate of about 166 k€ per day opposed to the PSV estimated charter rate of about 10 k€. So, in theory the PSV could be operational for 16.6 days for every day it reduces the HLV operational time. Also, note that the average cost increase remains about 0.02 €/MWh for every 50 km the farm is positioned further away from shore.

Gearbox and gearbox generator

The gearbox and GB generator both come at the same cost as the direct drive. The slightly smaller PSV for the gearbox and GB generator is not of sufficient difference to cause a noticeable decline in cost. Still the cost of configuration 1 is equal for all other components. This means that the gearbox and GB generator replacement operations performed by configuration 2 are up to 6 to 8% less costly.

7.3.4. Influence of sailing speed

In previous sections it was discussed what effect sailing speed and configuration have on the three main output values separately. However, there is also a correlation between the output values. For example, the increase in sailing speed can be beneficial in terms of FOWT downtime, but disadvantageous considering the energy demand and emissions (with the exception of hydrogen). There are three correlations between the three output values; FOWT downtime - energy demand, FOWT downtime - cost and energy demand - cost. The FOWT downtime - energy demand correlation has a reversed reaction on the increase in sailing speed. This reversed reaction creates a Pareto front between the two output variables for each farm, with an example shown in figure 7.1, which visualises the potential trade-offs. This front is shown in figure 7.1 for farm A considering configuration 1 performing a blade replacement. The FOWT downtime - cost correlation is a linear trend, where the cost decreases if the FOWT downtime decreases and vice versa. This is expected as both output values show beneficial behaviour for increased sailing speeds. The last correlation, between energy demand and cost, also shows a Pareto front (see figure 7.2) regardless of vessel difference in sailing speed for configuration 2. Energy demand, which transfers to fuel cost, is directly linked to the total cost of the replacement operation. So, a trade-off can be made depending on priority between GHG emission due to energy demand and total cost. Note that it is likely that the front will move further to the right if GHG emission will be taxed. Further details and derivation regarding this hypothesis can found in section 9.3.3.

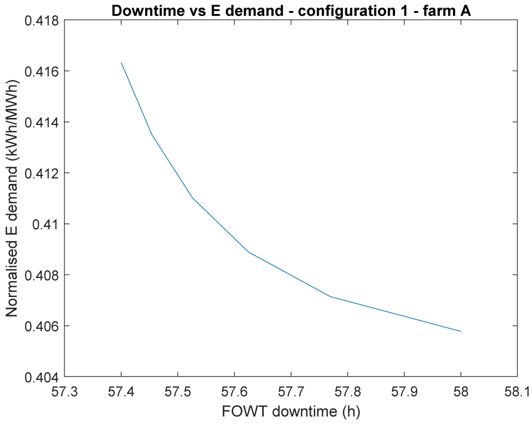

Figure 7.1: FOWT downtime vs energy demand for configuration 1 performing blade replacement in farm A.

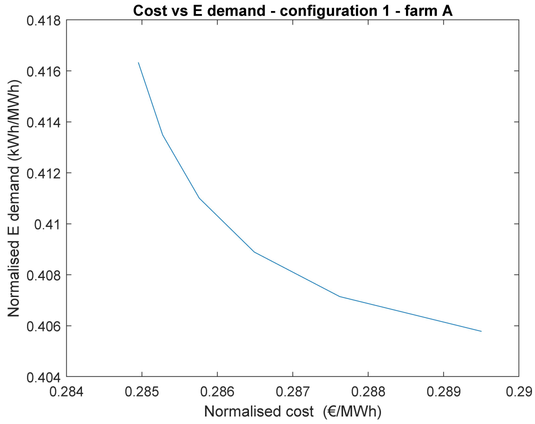

Figure 7.2: Cost vs energy demand for configuration 1 performing blade replacement in farm A.

7.4. Preventive maintenance

It is decided that the preventive maintenance is performed in either 30%, 50% or 100% of the FOWT farms for comparison. All preventive maintenance requests can be performed by the considered HLM configurations, except for two tasks for the blades in farm A, as these would result in overcapacity. Note that for preventive maintenance one component is replaced per FOWT, except for the blades. All three blades on a FOWT are replaced when preventive maintenance is performed. During this analysis the speed and key parameters of the support vessels involved are varied. Note that the blade feeder and HLV are not varied on their key parameters as these are fixed for these support vessel types.

7.4.1. Energy demand

Blades

The lowest energy demand for any of the three preventive maintenance tasks considering blade replacement is configuration 1. It does require at least 1.211 kWh/MWh for farm A, 1.212 kWh/MWh for farm B and 1.213 kWh/MWh for farm C. The increase in distance from shore does not increase the energy demand significantly, contrary to what was found in the breakdown maintenance section. This is regardless of the necessary additional trip to the shore for component replenishment as the DP operational profile becomes very dominant. Configuration 2 has approximately a two times higher energy demand compared to configuration 1. The increase in energy demand can be traced back to the blade carrier, which still provides no benefit. The HLV has to wait in the field for the blade carrier to return from port. This also adds to the energy demand compared to configuration 1, where the HLV is loaded in port and has a lower energy demand compared to waiting in field. Configuration 3 also shows an increase in energy demand of about 50% compared to configuration 1. This increase can also be devoted to the fact that the blade carriers do not sufficiently reduce the HLV energy demand to become beneficial.

Direct drive generator

The energy demand is again lowest for configuration 1 in all scenarios. However, the difference has become less compared to the other configurations. The energy demand for configuration 1 is about 0.404 kWh/MWh for all fields, being insignificantly smaller for farm A compared to farm C. Note that this value cannot be directly compared with the figures found for the blade replacements as these are valid for three blades per FOWT. Configuration 2 is still the configuration with the highest energy demand, which is about 22% higher compared to configuration 1. Configuration 3 comes in slightly better with an energy demand between 0.448 kWh/MWh for farm A and 0.450 kWh/MWh for farm C. This is still an increase of nearly 11% , which is yet again half the increase from configuration 1 to configuration 2. An interesting observation can be made when looking at the size of the vessels which are used in the lowest energy demand configurations. The PSVs that result in the lowest energy demand are the smallest vessels with a carrying capacity of one DD generator at the time. In terms of only transporting goods this is illogical. Nonetheless, the rationale of this choice can be found when including the time and energy demand in DP. The smaller vessels require a lot less energy in DP, which provides a significant advantage in terms of energy demand. The lowest energy demands are, similar to the breakdown maintenance, achieved at the lowest sailing speed.

Gearbox and gearbox-generator

Findings on the gearbox and GB generator show significant differences to the replacement of the DD generator. Configuration 1 still requires 0.404 kWh/Mwh, whereas the other configurations show a minor decrease in energy demand due to the slightly smaller PSV(s). The maximum reduction in energy demand compared to the DD generator is 1.4% for configuration 2 and 0.3% for configuration 3. This shows that the advantage of a smaller PSV becomes slightly more beneficial as the distance from shore increases. The increase in number of FOWTs shows to have less influence on the energy demand. Still, the lowest energy demand is found for the HLV combined with the smallest PSV(s), both at their lowest sailing speed.

7.4.2. Cost

Blade

The blade replacement is the least costly when performed by configuration 1. For farm A the cost, considering all cases, is 0.845 €/MWh, for farm B 0.847 €/MWh and for farm C 0.849 €/MWh. Configuration 2 and 3 both show an interesting feature where it is not the largest number of replacements that is the cheapest. Configuration 2 is the cheapest at the 50% replacement campaign for farm A and the 30% campaigns for farm B and C. The reason that these campaigns are slightly less costly, is the utilised cargo carrying capacity. For example, configuration 2 has a carrying capacity of 15 blades per trip, which is exactly one trip for the 30% case of farm B and two trips for the 30% case of farm C. This means that there is no overcapacity, i.e. unused carrying capacity, during the campaigns. In short, the remainder of the division, called modulus, should be as low as possible when considering the cost of the configurations 2 and 3. Yet, both configurations remain more expensive than configuration 1, at about 23% for configuration 2 and 13% for configuration 1. The analysis also shows that the number of trips to and from the site should be kept at a minimum.

Direct drive generator

The replacement campaigns in every case are the least costly when configuration 3 is chosen. The minimum cost is on average 0.262, 0.271 and 0.272 €/MWh for farm A, B and C respectively. Again, the lowest cost is found at the situation with the lowest modulus. Configuration 2 has the second lowest cost, indicating that the HLV operational time is still reduced enough to be less costly compared to configuration 1. However, adding a second PSV seems to reduce the HLV operational time so much more, that it is still beneficial from a cost perspective.

Gearbox and gearbox-generator

The general findings for the gearbox and GB generator are very comparable to the DD generator. Still, configuration 3 is the cheapest configuration, followed by configuration 2 and 1. The cost price remains equal for configuration 1, but drops at maximum 0.001 €/MWh for configuration 2 and 3. This slight drop is, again, caused by the slightly smaller vessels that can be used for the transport of the components. Still the cost is lowest if the modulus is lowest and the number of port visits is at a minimum. This is also visualised in figure 7.3.

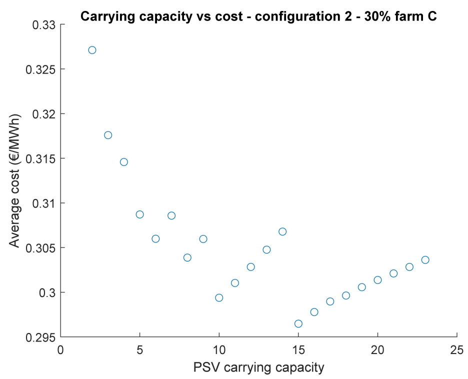

Figure 7.3: Carrying capacity vs cost for configuration 2 performing gearbox replacement.

7.4.3. Alternative fuel selection

From the previous sections it can be derived that there is not a single configuration that scores best in terms of cost and energy demand, with the exception of configuration 1 for the blade replacement campaigns. Configuration 2 shows the worst performance compared to the other configurations and will therefore be excluded from further optimisation. With this exclusion it can be said that configuration 1 has the lowest energy demand, but highest cost compared to configuration 2. Cost is already at its lowest, with the selection of MGO as reference fuel. Thus, decreasing the cost of both configurations is not possible. Also, the energy demand cannot be reduced, but the GHG emission arising from it can. The reduction in GHG emission is paired with the increase in cost. The cost increase should remain below the other configurations in order to remain economically viable. Configuration 2 is shown for five fuels presented in table 4.4. Hydrogen provides the greatest reduction in GHG emission, but cost rises 25.6% for configuration 2. Moreover, not all maintenance cases can be performed anymore due to a lack in available bunker capacity. Even so much that the replacement of 10 GB generators in farm A is not possible anymore, without an additional port visit to bunker. Methanol and ammonia also show an increase in price of 16 and 17% respectively, making both more expensive than configuration 1 running on MGO. LNG on the other hand can provide a good alternative, with cost approximately equal to that of MGO. This makes it a suitable solution for both configurations, while the GHG emission drops about 32%. A disadvantage of this fuel is that it also takes up more volume than MGO, resulting in a lower autonomy. However, this has far less impact compared to hydrogen.

7.5. Closing remarks

In this chapter an analysis was made of the different HLM configurations for the FOWT farms A, B and C. The FOWT downtime for the breakdown maintenance can be lowered for the different configurations by increasing the sailing speed. However, this does create a Pareto front between sailing speed and energy demand, and also energy demand and cost. Configuration 2 has an advantage over configuration 1 as it is able to run processes parallel to each other. On the other hand, configuration 1 has the lowest energy for any replacement of the components. The cost of the breakdown maintenance tasks is lowest for configuration 2 as it reduces the operational time of the HLV, which is the dominant cost item. An exception is the blade replacement operation where the relative expensive blade carrier is not beneficial in terms of cost.

The configurations for the preventive maintenance tasks were compared on energy demand and cost. It was found that the blade replacement can best be performed by configuration 1 based on both parameters. Configuration 2 showed to be the worst performing configuration for farm B and C where it had the highest energy demand and cost. For farm A, the cost is slightly below the highest cost, but still well above the lowest cost. Configuration 3 is the least costly option, but the energy demand is in between configuration 1 and 2. The lowest energy demand for the component replacement campaigns is configuration 1, which is the most costly configuration for farm A and the second most costly for farms B and C. Cost is in general the least when there is the least amount of overcapacity and the number of trips is at a minimum.

Next to energy demand there is the choice for an alternative fuel to lower the GHG emission. Hydrogen would have the most impact, but will lower the autonomy in a very serious way. Moreover, the cost would increase above the most expensive configuration, which is also the case for ammonia or methanol. Choosing LNG as alternative fuel leads to almost no cost increase, while lowering the GHG emission by about 32%, making it the most suitable alternative.

8

Tow to port maintenance strategies

8.1. Introduction

This chapter provides the answer to the following sub-question:

> *What is the most effective solution to improve the sustainability of major component replacements in a floating offshore wind farm, considering utilisation and parametric design of support vessels used in the tow to port strategy?*

The aim of this chapter is to provide a detailed view on the different TTPM configurations, which are listed in section 4.6. First, an elaborate overview is provided on the analysis parameters used for the different maintenance tasks. Thereafter, the configurations are compared on breakdown maintenance tasks for different FOWT farms, followed by the impact of the towing speed in relation to the different analysis parameters. The configurations are also compared on different preventive maintenance tasks for the different FOWT farms, followed by an analysis on the effects of the use of alternative fuels. The chapter is closed with a brief summary.

8.2. Analysis parameters

The analysis parameters for the TTPM strategies are equal to the HLM strategies, which are FOWT downtime, energy demand and cost. The FOWT downtime is the time between FOWT failure and repair, making it operational again. The energy demand is the amount of energy necessary to complete the task and 'replaces' the GHG emissions. The GHG emission can be calculated with equation 4.6, which shows that the other variables can be factorised per fuel type. The cost in this chapter is also based on the baseline fuel MGO.

FOWT downtime will not be considered for the preventive maintenance tasks as the assumption is made that the FOWT is shutdown as soon as the AHTS is in position next to the FOWT and on DP. This will lead to an equal FOWT downtime for all preventive maintenance tasks. Another assumption that is made, is that every breakdown is repaired directly and that not a minimum number of failures has to occur to start a breakdown maintenance campaign.

The energy demand and cost are provided in kWh/MWh and €/MWh respectively. The MWh is the energy produced during the operational lifetime of the FOWT(s) that underwent maintenance. The produced energy estimation is based on a 15 MW FOWT, with a capacity factor of 50% and an expected lifetime of 25 years. The port crane which is used in the TTPM operations is included in the cost calculations, but will not be included in the energy demand calculations. Reasoning behind this decision is that large crawler cranes can be electrified and in theory could run on the energy generated by the FOWT wind farm [40].

8.3. Breakdown maintenance

During the breakdown maintenance the FOWT is towed back to port, where the replacement takes 52 hours [16]. This means that the procedure is the same for all components. However, energy demand and cost do vary for different floater types and are therefore discussed separately. Configuration 4 and 5 are both considered for the breakdown maintenance, whereas configuration 6 and 7 are not. The latter two are meant for larger preventive maintenance requests, thus not suitable for breakdown maintenance. Configuration 4 utilises one AHTS and one assisting AHTS. Both sail out to the FOWT, where upon arrival the AHTS connects its towing line to the FOWT. The assisting FOWT starts to disconnect the mooring lines of the FOWT, which is estimated to take 8 h per line. This estimation is based on the Hywind Scotland environmental report, which is an existing pre-commercial FOWT farm [57]. After all lines are hooked off the AHTS tows the FOWT to the O&M port. The assisting AHTS sails straight to port. After the replacement is performed by a land based port crane, the FOWT is towed out again. The assisting AHTS leaves port, and the port idle condition, to arrive at the same time as the towed FOWT in field. The FOWT is hooked up again with the same time consumption per line as for hook off. When this is finished the AHTS and assisting AHTS return to port, where the task is finished as soon as they enter. Configuration 5 follows the same procedure, the only difference is that hook on and off can be performed faster with the help of an additional assisting AHTS. The parameters that are varied during this analysis are the sailing speed for the vessels involved and the bollard pull for the AHTS vessel.

8.3.1. Downtime

SPAR

The FOWT downtime for the SPAR floater is at least 101.9 h for farm A and increases to 109.5 h and 119.0 h for farm B and C respectively, when configuration 4 is used. In all cases, the vessels sail at maximum speed and the FOWT is towed at 13 km/h by the AHTS which has a BP of 400 t. Note that the assumption is made that the FOWT has no restriction on maximum towing speed. Taking a closer look at the FOWT downtimes, it shows there is a near linear relation between the FOWT farm distance from shore and the FOWT downtime itself.

Configuration 5 does show an improvement in terms of FOWT downtime, lowering it to 85.9 h, 93.5 h and 103.0 h for farm A, B and C respectively. The FOWT downtime reduction is 16 h for all the cases compared to the previous configuration. This can be explained by the fact that the additional assisting AHTS reduces 8 hours of FOWT downtime per hook on/off.

Semi-submersible

The minimum FOWT downtime of the semi-submersible floater is slightly larger compared to the SPAR floater. This is due to the greater BP requirements. The same AHTS with a BP of 400 t gets the FOWT up to a speed of 9 km/h, which is 4 km/h less than the SPAR floater. The FOWT downtimes when utilising configuration 4 are 102.58 h, 112.90 h and 125.79 h for farms A, B and C respectively. From a relative point of view there is an increase visible that is just 0.67% for farm A, which rises to 5.74% for farm C. This relative increase is explainable as the towing speed has more influence on the farm furthest away from shore.

Configuration 5 still shows the same effect with a reduction of 16 h for all cases. This reduction is enough to provide a FOWT downtime shorter than configuration 4 for the SPAR floater.

8.3.2. Energy demand

SPAR

The minimum energy demand of configuration 4 is 0.586 kWh/MWh for farm A, 0.627 kWh/MWh for farm B and 0.680 kWh/MWh considering farm C. Contrary to the FOWT downtime, all vessels sail at their lowest speed and the minimum towing speed of 2 km/h is achieved by the smallest 120 t BP AHTS. Despite all farms having the lowest energy demand using the same support fleet compositions, it indicates that there is a relatively large increase in energy demand as the FOWT farm moves further away from the O&M port.

Configuration 5 does show to have an advantage over configuration 4, as energy demand drops approximately 0.073 kWh/MWh, 0.051 kWh/MWh and 0.025 kWh/MWh for farm A, B and C respectively. This decrease in energy demand is not expected with an additional vessel being utilised. However, it can be explained when a closer look is taken to the total time spent in DP during the hook on/off operations. For configuration 4 the combined time in DP is 96 h, while configuration 5 has a combined time in DP of 80 h. This indicates that the reduction in DP outweighs the additional energy demand of the second assisting AHTS. This is also visible comparing the different farms, where the advantage is considerably less for farm C compared to farm A. This is due to the fact that the fixed reduction in DP becomes less dominant when the distance from shore increases.

Semi-submersible
Equally to the FOWT downtime, the minimum energy demand increases due to the greater BP requirements. The minimum energy demand for configuration 4 with an AHTS of 220 t BP, is 0.748 kWh/Mwh for farm A, 0.802 kWh/Mwh for farm B and 0.870 kWh/Mwh for farm C. This is an increase of approximately 28% for all farms compared to the SPAR cases.
Configuration 5 is still a preferred option in terms of energy demand with a minimum energy demand of 0.624 kWh/Mwh, 0.701 kWh/Mwh and 0.798 kWh/MWh. This is expected as the port idle time of the additional AHTS does not increase for the minimum energy demand case. Comparing the outcomes of configuration 5 to the SPAR case, it is clear that the average increase in energy demand is still 22%. Despite the increase in energy demand, it is possible to use the hydrogen as fuel. This fuel has the lowest LHV, but results in a complete removal of GHG emissions.

8.3.3. Cost

SPAR
Configuration 4 has a minimum cost of 0.128 €/MWh for farm A, which increases up to 0.148 €/MWh and 0.172 €/MWh for farm B and C respectively. This shows that the prolonged operational time of the vessels increases the cost in a linear manner.
Configuration 5 has a larger minimum cost of 0.146 €/MWh, 0.174 €/MWh and 0.208 €/MWh for farms A, B and C respectively. The additional assisting AHTS increases the total operational time and now has become a disadvantage in terms of cost. As stated before, the charter rate is mainly based on the operational time of the vessels. To put the increase in perspective the cost for farm C increases just short of 60 k€ on a 280 k€ operation.

Semi-submersible
The larger vessel required for the towing of the semi-submersible floater also has an effect on the cost of the operation. The increase in cost for configuration 4 is 0.016 €/MWh for farm A, 0.037 €/MWh for farm B and 0.047 €/MWh for farm C, compared to the SPAR case. This makes the semi-submersible floater on average 25% more expensive considering configuration 4.
Configuration 5 encounters the same effect of the larger AHTS and has an average cost increase of 0.025 €/MWh compared to the SPAR case, which is about 18%. The increase being relatively lower is caused by the cost of the AHTS being less dominant in this configuration, where the assisting AHTS remains equal. Yet, the increase must not be underestimated. For example, the total cost for farm C is about 280 k€ for the entire operation considering configuration 4. This increases to more than 410 k€ for the same operation performed on a semi-submersible by configuration 5, which is a difference of 131 k€.

8.3.4. Influence of towing speed

In this section the influence of towing speed is discussed, as further analysis indicates that the sailing speed has a lesser impact on the output values, compared to the towing speed. By increasing the towing speed, FOWT downtime and total cost drop, but on the other hand the energy demand and thus GHG emission (except for hydrogen) increases significantly. This leads to three correlations, which are FOWT downtime - energy demand, FOWT downtime - cost and energy demand - cost. The first one, FOWT downtime - energy demand, has a reversed effect on the towing speed, which leads to a Pareto front, shown in figure 8.1 for farm A, configuration 4. This front provides the potential trade-offs between the two output values for a specific combination of configuration and farm. The second correlation that can be made is the FOWT downtime - cost, which shows something remarkable. The reduction in FOWT downtime, and thus operational time of the vessels, does not result in a linear reduction in cost. This is somewhat odd as this was the case for the vessels in the HLM strategy. An explanation for this observation is that the charter rate without fuel consumption is low as it is a relatively small vessel. However, the fuel consumption of the vessel is relatively high, especially during towing operations at higher speeds. This leads to a situation where the fuel consumption becomes dominant in the charter rate, which leads to a parabola, considering the cost vs towing speed. This shows once more that the Royal IHC in-house cost estimation tool is suitable to get a general view on the charter rate, but is less

appropriate for the purpose it is used for now. The FOWT downtime - cost correlation for configuration 4, farm A is shown in figure 8.2. The third correlation, energy demand - cost, also shows to have a Pareto front at lower towing speeds, but has a slight trend upwards again for higher towing speeds. This effect is still due to the increase in cost at higher towing speeds.
Despite the less optimal cost estimation model, it is still clear that there is a wicked problem at hand. This problem does not have one solution and trade-offs have to be made based on the priorities the output values are given.

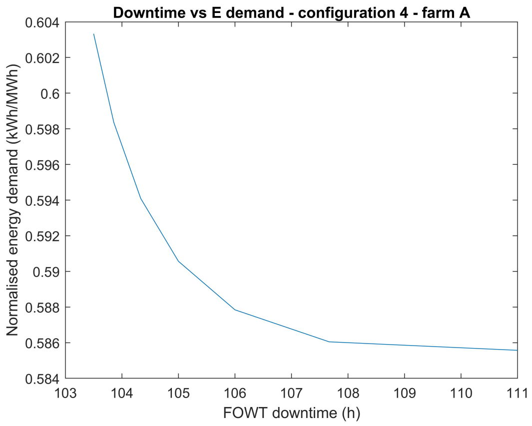

Figure 8.1: FOWT downtime vs energy demand for configuration 1 performing component replacement in farm A.

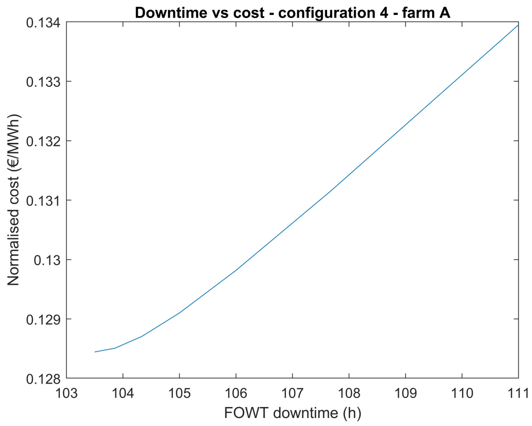

Figure 8.2: FOWT downtime vs cost for configuration 1 performing component replacement in farm A.

8.4. Preventive maintenance

Configuration 4 to 7 are able to perform preventive maintenance tasks for the FOWT farms. Again either 30%, 50% or 100% of the FOWT farms undergoes major component replacement. Note that for the blade replacement it is assumed that all three blades are replaced, which will take up 156 h in port. During this analysis the sailing speed of the support vessels involved is varied, together with the BP of the AHTS.

8.4.1. Energy demand

Non-blade components

Configuration 4 has the highest energy demand considering farm A and B, when considering SPAR floaters. The energy demand is roughly 0.583 kWh/MWh for farm A and 0.610 kWh/MWh for farm B. There is a less steep increase in energy demand (0.644 kWh/MWh) as the number of FOWTs for component replacement rises, which leads to a better energy demand for farm C, where it outperforms configuration 6 (0.653 kWh/MWh). The less steep increase in energy demand can be explained by the fact that the vessels do not first return to port when the previous FOWT is hooked on again after repair. Instead, the vessels make a direct transit to the next FOWT, thus resulting in a lower energy demand for a larger number of maintenance requests. Configuration 5 remains to be advantageous in terms of energy demand compared to configuration 4. The reasoning behind this is similar to that discussed in section 8.3.2. Configuration 5 also shows a decline in normalised energy demand as the maintenance request increases in size. This decline makes it the preferred configuration for farm C, where it has an energy demand of about 0.605 kWh/MWh. Configuration 6 and 7 have an opposite trend where the energy demand rises with the increase in number of FOWTs that undergo component replacement. This opposite trend is caused by the increase in port idle time as more FOWTs are being serviced. The increase in port idle time comes from the fact that every time a FOWT is towed to shore the assisting AHTS also goes to port, where it waits until the AHTS sails out again. This effect is noticeable as configuration 7 is the preferred configuration for farm A, where it has about 0.480 kWh/MWh and farm B has approximately 0.540 kWh/MWh. However, the opposite trend of configuration 7 has intersected with the trend of configuration 5 at farm C, where configuration 5 is preferred. Configuration 6 remains to be outperformed on all farms considering SPAR floaters by configuration 7 and even performs worse at farm C compared to the other configurations.

The semi-submersible floater, similar to what was found for the breakdown maintenance, demands more energy compared to the SPAR floater type. Configuration 4 and 6 both show the largest increase in energy demand, with about 0.160 kWh/MWh for farm A, 0.170 kWh/MWh for farm B and 0.185 kWh/MWh for farm C. This increase is caused by the extended time in DP for the larger AHTS, required to tow the FOWT to and from the O&M port. Nevertheless, when looking at the relative increase it is relatively stable at 22%. The same goes for configuration 5 and 7, but both only show an increase of roughly 18%. This results in an absolute energy demand of 0.110 kWh/MWh, 0.120 kWh/MWh and 0.135 kWh/MWh for farm A, B and C respectively. Despite the difference in absolute energy demand, the preferred configurations for the different farms remain equal to the configurations found for the SPAR floater cases.

Blades
The blade replacement has an interesting effect on the energy demand for the different configurations. Configuration 7 is now the preferred configuration for all farms considered. This is due to the fact that the energy demand for configuration 4 increases 8% to 9% compared to the non-blade component replacement. Also, configuration 5 shows a considerably higher cost ranging from 13% for farm C, up to 16% for farm A. Configuration 6 and 7 do not show any change in energy demand compared to the non-blade component replacement. This is expected as the in port repair time falls in between the activity of the two different tow in and tow out vessels. It must be noted that the energy demand of the port crane is not taken into account. So, the duration of the in port repair does not affect the energy demand in the end. The effect of the increased farm size and distance does also result in a relative variance when comparing configuration 4 and 5 to configuration 7. At farm A the difference compared to configuration 7 is 34% and 25% for configuration 4 and 5 respectively. This relative difference does change significantly when looking at farm C, where the difference is approximately 13% for configuration 4 and 11% of configuration 5. This demonstrates that the normalised energy demand of the replacement operation still drops if the number of FOWTs for service increases.

The semi-submersible floater type has the same occurrence, where the energy demand for configuration 6 and 7 remains equal to the non-blade component replacement. Moreover, the relative difference to configuration 4 and 5 is also similar to the figures found for the SPAR cases. Again, configuration 7 is the preferred configuration, in terms of energy demand, for all fields.

8.4.2. Cost

Non-blade components
In terms of cost, Farm A with SPAR floaters is best off, with configuration 7 with an average cost of 0.079 €/MWh. Configuration 7 shows a remarkable advantage of 38% cost reduction on configuration 4 and 47% on configuration 5. This large difference in caused by the more time efficient use of the vessel. However, the calculation model is also ”tricked” by configuration 6 and 7, because the tow out vessels only come into play after the first repair is performed. This means that during the first in port repair time no vessels are included in the cost calculations. A similar method can be applied for configuration 4 and 5, if every time a vessel is in port idle mode, it is removed from the charter and comes back in again when another operational profile is required. Despite this calculation ”trick” for both configuration 6 and 7, it is believed that an advantage would remain even when the port idle time during repair would be included, just less significant. Another, noticeable finding is that the average cost declines as the number of FOWTs for service increases. Nevertheless, the normalised preventive maintenance cost of farm A is roughly equal to the normalised breakdown maintenance cost. This does deviate rather quickly in the advantage of the preventive maintenance requests, as for farm B the preventive cost is about 5% less and 10% less for farm C. The least costly configuration for farm B and C is configuration 6. This configuration has the advantage that one assisting AHTS less has to remain in port idle condition till the FOWT is towed into port. This effect only becomes visible for FOWTs further away from shore, which leads to a prolonged towing time for the AHTS, where it is on average 4% less costly for farm B (0.104 €/MWh) and 9% less costly for farm C (0.134 €/MWh). For all the farms, configuration 4 is less costly than configuration 5, and becomes relatively less costly as the FOWT farms move further and the number of FOWTs increases.

The cost for the farms that posses semi-submersible floaters is on average 0.020 €/MWh more for farm A, 0.030 €/MWh more for farm B and 0.040 €/MWh more for farm C. It must be noted that, generally speaking, the increase in cost is about twice as large for configuration 4 and 5 compared to configuration 6 and 7. Configuration 7 is still the least costly for farm A, as is configuration 6 for farm C. It is interesting to see that configuration 6 and 7 have a roughly equal cost at farm B. This indicates that farm B is near a tipping point for configuration 6 and 7, which was also visible for the SPAR floater type.

Blades
The replacement of three blades is more costly than the replacement of a single component. Configuration 4 and 5 are the most costly configurations. The configurations were already the most costly for the single component replacements, but the difference between the lower cost configurations has increased. This is due to the fact that the other configurations do not include the port idle time of the repair as previously discussed. Contrary to the energy demand, configuration 6 and 7 do show a difference, compared to the single component replacement. This is due to the port crane cost which is included in the calculations, which results in an increase of about 0.020 €/MWh. Configuration 7 is still the lowest cost configuration for farm A, with an average cost of 0.021 €/MWh. This does change for farm B (0.122 €/MWh) and C (0.144 €/MWh), where configuration 6 is the most advantageous configuration.

In general the same remarks apply for the semi-submersible floater type as for the SPAR floater type. The only difference is that the minimum cost is greater as greater BP is required. The minimum lowest cost is 0.112 €/MWh, 0.148 €/MWh and 0.144 €/MWh for farm A, B and C respectively.

8.4.3. Alternative fuel selection

The lowest energy demand and cost are found for configuration 6 and 7. This provides the option to choose an alternative fuel in order to lower the GHG emissions, as long as the cost remains below configurations 4 and 5. The advantage of the TTPM strategies is that all vessels visit the O&M port at relatively great frequency. This solves the potential bunker capacity problem encountered for the HLM strategies and makes that configuration 6 and 7 can both use hydrogen for all cases as the preferred fuel in terms of GHG emission. However, in terms of cost it becomes around 3% more expensive. While this is a relatively low increase, it surpasses the set limit. Other fuels that prove a good alternative are methanol and ammonia. Both do increase the cost significantly, yet the cost for the ammonia stays 9% below configuration 4 and methanol 7%. Methanol shows a decrease of 8% in GHG emission, while ammonia would lead to a 92% reduction. LNG can also be considered as an alternative fuel to reduce the GHG emission, with cost being about equal to MGO usage. The implementation of LNG would lead to a drop of approximately 32% in GHG emission.
With this information, it remains odd to see that ship owners are moving to methanol engines. As an example, Royal IHC has received multiple requests from the industry for the implementation of such engines. A reason why this is preferred over LNG and ammonia, is that it is not toxic and relatively easy to handle. Moreover, MGO facilities can be easier retrofitted to methanol than to LNG, allowing for a better infrastructure. Another advantage over LNG is that the required volume is less, leaving more space for other supply operations [48].

8.5. Closing remarks

In this chapter four different TTPM configurations were compared on three different FOWT farms of different size and distances from shore. The configurations were analysed on energy demand and cost for preventive maintenance and additional FOWT downtime for the breakdown maintenance. It was found that for the breakdown maintenance configuration 5 was preferred in terms of energy demand and FOWT downtime. A disadvantage of the additional assisting AHTS is that the cost becomes higher, compared to configuration 4. The influence of towing speed was discussed separately as this has more effect on the operation than sailing speed. The increase in towing speed has a positive effect on FOWT downtime and cost (to a certain extend), but has a negative effect on the energy demand. The trade-offs between FOWT downtime - energy demand and cost - energy demand can be visualised in a Pareto front. Configuration 7 is preferred in terms of cost and energy demand for the preventive maintenance tasks at farm A. This switches to configuration 6 if farms B and C are considered. It must be noted that the large advantage compared to configuration 4 and 5, partially arises from excluding port idle time from the calculations. Lastly, alternative fuels were implemented to see what the maximum GHG reduction would be without exceeding the cost of configuration 4 or 5. The fuels with great potential, that meet this standard, are LNG, methanol and ammonia.

9

Hybrid maintenance strategies

9.1. Introduction

This chapter provides the answer to the following sub-question:

> *What is the most effective solution to improve the sustainability of major component replacements in a floating offshore wind farm, considering utilisation and parametric design of support vessels used in the combined maintenance strategies?*

In the previous chapters different maintenance strategies were discussed and compared to configurations regarding the same strategy. However, it is also interesting to see how the different strategies relate to each other. This chapter compares the different strategy configurations for breakdown maintenance and preventive maintenance tasks. Additionally, a future outlook is provided on new innovations that are entering the market, or are potentially beneficial. Also, the effect of new legislation on emission allowances is discussed. The chapter is finalised with a conclusion of the findings.

9.2. Comparison of strategies

In total, seven different configurations are considered in this report. Three of them are HLM strategies and four are TTPM strategies. The HLM strategies and TTPM strategies are both discussed separately in chapter 7 and 8. However, both strategies have their advantages and disadvantages and the industry seems to be moving towards, or at least is very interested in, the HLM strategy [71]. Yet, it is likely that a hybrid solution which will include both options will be used depending on the nature of the required repair [63]. This hybrid solution has the potential to utilise the advantages of both strategies to a maximum. However, the configurations and task division between these strategies is unclear. Therefore, the configurations will be compared on the analysis parameters, which were also used in previous chapters. For breakdown maintenance these are FOWT downtime, cost and energy demand. For the preventive maintenance the configurations are compared on terms of cost and energy demand, with the additional analysis value; operational duration. The operational duration provides information on the duration of the replacement campaigns and the actual realization of it.

9.2.1. Breakdown maintenance

Downtime

The FOWT downtime is one of the most important parameters as it directly results in lost revenue [68]. Comparing the TTPM and HLM strategies, it becomes clear that all configurations of the HLM outperform every TTPM configuration. The best configuration of the HLM strategy is configuration 2, with a FOWT downtime of 57.4 h, 58.8 h and 60.6 h for farm A, B and C respectively. Whereas on the other hand the FOWT downtime of the best TPPM configuration, configuration 5, is 85.9 h, 93.5 h and 103.0 h for the same farms. A noticeable difference to start with is the influence of the distance to shore for both configurations. The HLM configuration has an increase in FOWT downtime of 5.5% (3 h) comparing farm A to farm C, whereas this same comparison leads to a 19.9% (17 h) increase in FOWT downtime in the TTPM configuration. A clear difference in operational profile does clarify where the additional time is spent for the TTPM configuration. It is not the towing time, but rather the hook on/off time which takes up 8 h per line. The hook off and hook on operation combined takes up 32 hours. Even when an additional assisting AHTS would be added to the TTPM configuration, it would still result in a FOWT downtime difference of 12.5 h for farm A, 18.7 h for farm B and 26.4 h for farm C. Another solution to lower the FOWT downtime of the TTPM strategy is to implement some kind of quick connection mooring wires. This hypothesis will be further discussed in section 9.3.2. For now the HLM strategy is preferred over the TTPM strategy in terms of FOWT downtime.

Energy demand
The energy demand is lowest for HLM configuration 1, where only one HLV sails to the field to replace the component. The configuration with the lowest energy demand in the TTPM strategy is configuration 5, which utilises one AHTS and two smaller assisting AHTS vessels. Despite the fact that the TTPM strategy uses smaller vessels it does not outperform the HLM strategy. The extended operational time together with the relatively high energy consumption during towage leads to a relatively higher energy demand. The difference is about 26% for farm A and rises to 54% for farm C considering the SPAR floater type. When considering the larger semi-submersible floater, the energy demand increases significantly with a difference of 54% for farm A and 87% for farm C. This shows that both the distance from shore as well as the floater type can have a considerable impact for the TTPM strategy. In contrast, the HLM strategy is not affected by the floater choice and shows to experience less influence of the increased sailing distance. In short, the HLM strategy performs better on all farms considered and its energy demand depends less on external factors. If the vessels are solely used for breakdown maintenance, both configurations can use hydrogen as fuel without bunker capacity shortage. The use of (green) hydrogen will lead to a GHG free operation for both strategies.

Cost
In terms of cost, the TTPM strategies have a clear advantage on even the least costly HLM strategy. TTPM configuration 4 has a minimum cost for SPAR floater types of 0.128 €/MWh, 0.148 €/MWh and 0.172 €/MWh for farm A, B and C respectively. This does increase when the semi-submersible floater is considered. However, the HLM approach remains at least 32% more costly regardless of floater type and distance from shore. When considering a SPAR floater in farm A, the cost difference goes as high as 55%. The main difference in cost is due to the charter rate of the HLV, which is estimated at 166 k€ per day, while even the largest 400 t BP AHTS vessels are estimated to have a day rate of 50 k€. This implies that for every hour the HLV is operational, an AHTS can be operational for three hours and still be more cost efficient. A smaller crane vessel with a lower day rate could potentially make the HLM strategy more attractive. Nonetheless, the day rate reduction has to drop severely to out compete the TTPM strategy.

Recommendation on breakdown maintenance
For the breakdown maintenance the HLM strategy seems to outperform the TTPM strategy on two of the three analysis parameters. Therefore, it would be logical to favour the HLM strategy over the TTPM strategy. However, this statement comes with two important remarks. First, the vessel availability of (monohull) HLVs is currently very low, as only a handful were identified during this study. It is likely that this will increase the day rate of such vessels even more. This will also affect the FOWT downtime as these vessels will not always be directly available. Admittedly, there are also clear indications that there will be a shortage in the AHTS market, with more and larger FOWT projects being brought to the market [30]. Secondly, it is expected that currently the cost of the operations has a higher priority compared to the other analysis parameters. Reasoning behind this, is that the levelised cost of energy is still relatively high compared to the fixed offshore wind industry. To remain economically attractive, cost should be kept as low as possible. In 2019 the delivery price for fixed offshore wind was between 42 €/MWh and 52 €/MWh, while the FOWT delivery price was estimated to be twice that amount [58].

9.2.2. Preventive maintenance

Energy demand
In terms of energy demand there is not a single strategy of configurations which outperforms the other available options. The HLM strategy, mainly configuration 1, does require the lowest amount of energy for the replacement of the gearbox, GB generator and DD generator. The difference compared to the

TTPM configuration with the lowest energy demand is about 30% for farm A, 39% for farm B and 47% for farm C. This demonstrates that the HLM strategy becomes even more favourable as the distance from shore increases. However, when all blade replacement campaigns are considered the TTPM configuration, configuration 7, is outperforming the HLM strategy. The advantage is around 52% for farm A and declines to 38% for farm C, for the semi-submersible floater type. This significant difference is caused by the extended DP time required for the HLV as all three blades have to be replaced. During the TTPM strategy, the vessels continue to tow in or out FOWTs while the port crane performs the repair. Briefly stated, the TTPM strategy is preferred for the blade replacement campaigns, whereas the HLM approach shows a clear advantage for replacement campaigns of components other than blades.

Cost

The cost is lowest for the TTPM strategy in all considered cases. This does agree with the findings for the breakdown maintenance, but the gap between the two strategies increases significantly when more FOWTs are serviced or when a blade replacement is considered. The non-blade component replacement is about 2.8 times less costly for farm A, but lowers slightly when the distance from shore increases to 1.4 times the cost for farm C. The blade replacement campaigns do demonstrate an even larger difference. The extended time needed by the HLV to perform the blade replacements, results in a significant difference where the TTPM strategy is 7.7 times less costly at farm A and 5 times less costly at farm C. However, it must be noted the TTPM method slightly ”tricks” the calculation model, as the port idle time is excluded in the calculations. More information on this matter can be found in section 8.4.2. However, a considerable advantage is still visible when comparing the HLM strategy to other TTPM configurations, which do not exclude the port idle time.

Operational duration

The operational duration is shorter for the TTPM strategy as three processes can run parallel to each other, when considering configuration 7. The tow in vessel brings the FOWTs to the O&M port and the tow out vessel brings the FOWTs with replaced components back to the field. The repairs are conducted in port by the available port cranes. For HLM configurations most of the processes are in a more serial order. This is slightly reduced by the utilisation of PSVs, but still operations with an extended duration cannot take place parallel. This would suggest that the TTPM strategy is the preferred strategy. However, this is not a fair comparison when the practical side is considered, especially considering farm A. The fastest TTPM configuration requires roughly 17 h to tow in a FOWT from farm A. This means that the O&M port must have the facilities to handle three to four FOWTs at the same time to avoid congestion and increased FOWT downtime. Even up to ten port cranes are needed when all blades have to be replaced. This also highlights another important aspect of both strategies. For the HLM strategy the FOWT has a downtime of 52 h, regardless of the distance from shore or floater type when one component has to be replaced. The same FOWT that is serviced by the TTPM strategy will be out of service for at least 86 h in farm A considering the SPAR type floater. This can even increase to a maximum of 113 h for the semi-submersible floater in farm C, which is more than twice the FOWT downtime caused by the HLM strategy.

Recommendation for preventive maintenance

Based on the analysis parameters, the TTPM strategy slightly outperforms the HLM strategy. Still, the HLM also provides a good solution, especially for the replacement campaign of non-blade components. It also provides the benefit of lower FOWT downtime, as the replacement can be performed on site. The TTPM has the advantage that the cost of the campaigns is significantly lower for all considered scenarios. It must be noted that the TTPM strategy does depend on several external factors. The first and perhaps most important factor is the availability of port cranes and infrastructure. If the O&M port does not posses enough large crawler cranes the TTPM strategy cannot be conducted, or will experience an increase in FOWT downtime. Another aspect that must be considered is the quayside availability within the port as the floaters will take up a significant quayside area and require sufficient depth. These requirements can make it impossible to perform the TTPM strategy at all. Nonetheless, if these requirements are satisfied, the TTPM strategy is considered the optimal strategy.

9.3. Future outlooks

In the previous sections configurations were tested and compared based on more conventional and well known methods. However, as time progresses new innovations are brought to the market and what is now considered less conventional could become the standard in the future. Therefore it is deemed important to see what the potential effect could be, when 'non-conventional' methods are introduced. Additionally, new legislation could also affect the outcome of the comparison between different configurations. Therefore, two different innovations, one HLM innovation and one TTPM innovation, are included in this part of the study, together with the potential effect of emission allowances.

9.3.1. Self hoisting crane

The first innovation that is considered is the self hoisting crane and its close relative; the climbing crane, which will be implemented in the HLM strategy. The self hoisting crane is a compact foldable crane which is hoisted on top of the nacelle by a taut-wire system. Once it is mounted it is unfolded and prepared to lift the components on or off the FOWT. When the replacement is finished the crane can be brought down in the reversed order of installation. This type of innovation is currently used in the onshore wind market, where it has performed over 800 gearbox replacements worldwide [41]. The self climbing crane is fundamentally the same concept, but rather than being hoisted on top of the nacelle it climbs along the tower to the top of the WT, by the means of a pinning system. This system is a more recent development, but has shown to be a proven concept as three onshore WTs were built last year using this concept [18]. The advantage of this system is that the crane itself is positioned higher, reducing the required lifting height to just a few meters. This does make the HLV, the vessel with the highest day rate and average energy demand, redundant in a way. Also, it would allegedly increase the wind speed operation limits to 20 m/s [43].

Estimations

Currently, there are a number of suppliers in hoisting and climbing cranes, all providing different specifications. It is decided that a climbing crane would provide a better and more conservative estimation. The climbing crane concept is generally speaking less compact and provides a larger lifting capacity. Note that at this moment the maximum lifting capacity reported is 150 t [43]. Therefore, the assumption is made that further development will lead to a lifting capacity which is sufficient for the 15 MW WTs. The deck area needed for transport is estimated on ten truck loads, based on the supplier information of Mammoet and Lagerway [43][39]. It is estimated that one truck load has a footprint of 15 m^3, which is equal to the footprint of one TUE container. This would bring the required surface area to 150 m^3. The build up and build down time of the crane is estimated to be one day (24 h) [39]. Unfortunately, there was no information found on the cost of the crane use in an O&M scenario, but it is claimed that the installation cost of onshore WTs could be lowered 80% compared to the conventional installation method [15]. To still get an idea of the potential reduction it is assumed that the day rate is equal to the day rate of a large crawler crane in port.

Outcome

The climbing crane is compared for two extreme cases; the single breakdown maintenance located at farm A and the full replacement at farm C. In both cases the gearboxes are replaced.

At farm A a single component has to be replaced, which is performed by a PSV. This PSV has a carrying capacity of four GB generators or four gearboxes. Three of the four slots are assumed to be occupied by the self climbing crane. It is found that the downtime of the FOWT increases when using a self climbing crane, due to the additional build up and build down time. The FOWT downtime is at least 101 h, which is comparable to the TTPM strategy for the same scenario. The energy demand does decrease significantly as the HLV drops out of the configuration. The energy demand is estimated to be around 0.180 kWh/MWh, which is roughly half the energy demand of configuration 1. The cost also decreases significantly and does outperform all other options discussed in this report. The cost is estimated to be around 0.062 €/MWh, but this relies heavily on the day rate assumption of the crane itself.

Farm C undergoes full replacement of the gearboxes, which will be performed by a PSV with a carrying capacity of 13 gearboxes. Three of these slots will again be occupied by the self climbing crane. This leads to two interesting findings. First, the energy demand drops roughly 43% compared to configuration 2, which involves a HLV and one PSV. This shows that the prolonged time in DP influences the outcome in a considerable way. To put this in perspective, in configuration 2 the PSV takes up 20% of the total energy demand. Secondly, the cost is lower than all other configurations. This is caused by the fact that the PSV has the lowest day rate of all vessel types, together with the cost assumptions for the crane.

Figure 9.1: The Lagerwey self climbing crane [39].

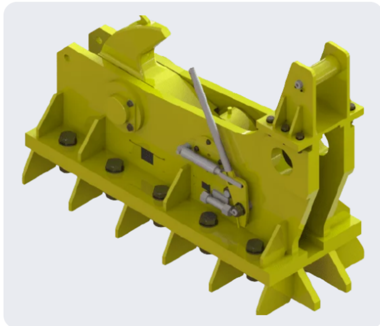

Figure 9.2: An example of a quick release offshore hook [22].

9.3.2. Quick (dis)connection mooring system

In section 9.2.1 it became clear that the hook on and hook off time in the TTPM strategy has a negative effect on the downtime of the FOWT. This is also pointed out by the Carbon trust reports, where it is even highlighted as the "most beneficial technology" for the TTPM strategy [63]. Currently, there is no such product on the market that is suitable for long term usage. A product that could be interesting is the quick release offshore hook, which is used in the FPSO industry to release mooring lines of a shuttle tanker. Figure 9.2, shows an example of a quick release offshore hook. Such a system allows a line to be released in moments [22]. However, this would perhaps become a dangerous exercise with steel mooring lines, but it shows that a faster release option could be possible.

Estimations

As there is no one-to-one product available, estimations and assumptions have to be made. The first assumption is that the use of the quick (dis)connection system does not require any additional equipment that could potentially alter the AHTS design and/or parameterisation. The second assumption is that the quick (dis)connection system possesses the ability to decrease the hook on/off time by 50% making it 4 h per line.

Outcomes

Just as for the climbing crane, the quick (dis)connection mooring system is compared on the two extreme cases, for gearbox replacements. This is the breakdown maintenance task in farm A and the entire field service at farm C. Both farms will be serviced by configuration 5, which already had the lowest FOWT downtime of the TTPM configurations.

The implementation of the quick (dis)connection mooring system does result in a minimum FOWT downtime of 69.9 h, when considering the breakdown in farm A. This is 16 h below minimum FOWT downtime of the 'normal' scenario. The energy demand is also an aspect that is influenced by the reduced hook on/off time. It drops by around 44%, as the DP operations are a high energy demand operation. The total cost is also reduced as the operational time of the vessel decreases. The minimum total cost is now 0.138 €/MWh, where it was 0.146 €/MWh.

The quick (dis)connection mooring system does also demonstrate its benefits in the full replacement campaign at farm C. It lets the energy demand still drop around 40 % and lowers the cost of the operation with roughly 0.010 €/MWh.

9.3.3. Emission allowance

Emission allowances are a market mechanism that gives CO_2 a price and creates incentives to reduce emissions in the most cost-effective manner. An example of such a system is the EU ETS, which has managed to bring down 42.8% of the CO_2 of energy intensive industries. Every year a cap is set for the total amount of CO_2 that can be emitted. A new climate law in the EU sets more ambitious climate goals and will also cover emissions from the maritime shipping industry [35].

Estimations

Every year the cap is lowered, thereby increasing the price. The last decade the prices stayed well below 40 € per tonne CO_2, but have risen in recent years up to 88 € per tonne in January 2022 [62]. Prices are expected to rise to 129 € per tonne in 2030 and even to 500 € per tonne in 2050 [50] [52]. It is decided that the 129 € per tonne CO_2 is a valid starting point for the comparison and impact. Note that the EU ETS is covering CO_2, whereas the calculations in this report are based on CO_{2eq}. The outcomes are therefore probably higher than seen in practice.

Outcomes

The estimations on emission allowances do increase the cost when the GHG emissions are higher. To compare the impact between the two strategies it is decided that the comparison will be based on the scenario where 50% of the gearboxes have to be replaced in farm B. It is decided that HLM configuration 1 will be compared to TTPM configuration 4 (semi-submersible floater), based on the differences in cost and energy demand.

When the emission allowances are excluded from the cost calculations it is found that configuration 1 has a minimum cost of 0.284 €/MWh and configuration 4 0.176 €/MWh. The emission allowances cause a rise in cost, which differs greatly between the two strategies. The HLM configuration has a relatively high cost and low GHG emissions compared to the TTPM configuration, leading to a cost increase of 4%. The TTPM configuration on the other hand demonstrates to be more affected by the emission allowances with a cost increase of more than 14%. Despite this variance in cost increase the HLM configuration is more costly (0.295 €/MWh), compared to the TTPM configuration (0.228 €/MWh). The analysis also showed that the cost increase is not sufficiently high, such that the alternative fuels; methanol, hydrogen or ammonia, provide a better solution from a cost perspective. LNG, which already proved to be a good candidate to replace the MGO, has now gained a bigger advantage. Cost was earlier estimated to be roughly equal, while after the implementation of emission allowance results show a 3 to 4% cost difference in the advantage of LNG.

9.4. Closing remarks

This chapter shows the contrast between the HLM and TTPM strategies discussed in the previous chapters. A comparison was performed for two different maintenance occurrences; the preventive maintenance and the breakdown maintenance, also referred to as corrective maintenance. The different strategies used for breakdown maintenance were compared on the analysis parameters FOWT downtime, cost and energy demand. For the preventive maintenance these were operational duration, cost and energy demand. It was found that the HLM strategy outperforms the TTPM strategy on two of the three analysis parameters and is therefore the most suitable option. However, it must be noted that it is not outperforming the TTPM strategy in terms of cost, which is a potentially important parameter. When considering the preventive maintenance tasks the TTPM has a slight advantage over the HLM strategy, especially when considering the full blade replacements. However, this advantage relies strongly on the assumption that the O&M port has unlimited resources available at all time.

This chapter also focuses on the potential future outlooks in terms of innovations and legislation. It is found that the climbing crane concept could make the HLV redundant in the HLM strategy, thereby lowering the cost and energy demand in a significant way. The quick (dis)connection mooring system also shows to be a valuable innovation. Especially energy demand is reduced greatly, due to the much shorter DP time of the vessels. Lastly, the emission allowances are discussed. These allowances result in an increase in cost, but will eventually not result in a HLM strategy that is less costly than the TTPM strategy. Moreover, LNG shows to become more favourable to MGO after the allowances. The cost of the alternative fuels; methanol, hydrogen and ammonia, is still relatively high compared to MGO and LNG and are therefore marked as not beneficial in terms of cost.

10
Conclusion

This report was written to find an answer to the following main research question:

What is the most effective maintenance strategy, in terms of sustainability and cost, for major component replacements in a floating offshore wind farm?

This question was raised by Royal IHC to get a head start in vessel concept design and product development for the upcoming floating offshore wind turbine (FOWT) market. The basis of the research method that has been used originates from the literature study which was performed in advance. One of the conclusions from the literature study was that there is a heavy lift maintenance (HLM) strategy and a tow to port maintenance (TTPM) strategy. In the HLM strategy a heavy lift vessel (HLV) is used to replace the major components on site, which can be supported by a "feeding" vessel, a platform supply vessel (PSV). The TTPM strategy uses an anchor handling tug supply (AHTS) vessel to tow the floating offshore wind turbine (FOWT) to port, where the major components can be replaced by a port crane.

A calculation model has been programmed and was used for this research to determine the CO_{2eq} emissions, power output of the FOWT farm, the FOWT downtime and the cost of the different strategies. It exists of six successive modules, each with their own functions. The first module sets the time frame for the simulation and introduces a wind and wave timeline based on historical weather data of an appointed geographical location. The second module introduces the FOWT farm parameters and determines the capacity factor. The third module simulates the amount of failures, which results in corrective maintenance tasks. It also provides the option to the user to include preventive maintenance tasks. The fourth module concerns the different selected operation and maintenance (O&M) strategies and the amount of energy required is determined. The fifth and sixth module generate data with regard to the CO_{2eq} emissions from vessel fuel consumption and the total cost of the operation, respectively. Note that the weather module is not used in this report, with the exception of the case study, as the weather module generates an arbitrary weather timeline, which influences the downtime of the vessels in an unrealistic way. There are three farms simulated for this report. A 10 FOWT farm 10 km from shore, a 50 FOWT farm 50 km from shore and a 100 FOWT farm 100km from shore.

For the HLM strategy the HLV and PSV had to be parameterised. However, for the HLV this was not possible due to the lack of HLVs with sufficient lifting height. Therefore, the newest wind installation vessel, the Les Alizés, of the Belgian company Jan de Nul is included in this study. The PSV could be parameterised as there were enough reference vessels available. The dimensions can be varied on the available deck area. However, the dimensions of the blades require a special kind of PSV, a blade carrier. This vessel is included in the model, but is not varied in size as the vessel ratios are bounded by the blade length. The AHTS vessel is also parameterised on the parameter bollard pull (BP), which is important to determine the towing speed of the FOWT. The assisting AHTS that (dis)connects the mooring lines can also be varied, but this has no influence on the operations. Therefore the assisting AHTS has an assumed BP of 120 t for the entire research. The Holtrop and Mennen method is used to determine the calm water resistance of the AHTS and PSV.

The model was tested to assess the quality and the outcomes. Unfortunately, it is not possible to validate the model against real life data as this is not (publicly) available. However, the model is verified in a case study followed by a sensitivity analysis. It was found that the wind and wave timeline are too stochastic to be used for prolonged operations with weather limits in place. The sensitivity analysis demonstrated that the HLM configuration reacts fairly sensitively to changes in repair time and DP power demand. The TTPM configuration is also sensitive to changes in DP energy demand, but shows less reaction to changes in repair time compared to the HLM configuration. The sensitivity of the model indicates that an under or overestimation in repair time and DP power demand could lead to a noticeable error. However, assumptions on these parameters are equal between the different configurations and strategies. This makes the model a reliable tool to compare different strategies to each other and potential new concepts. The outcomes from the sensitivity analysis were also used to verify the model. It was found that the whole model, with the exception of the weather module, could be verified and thus is well suited for this research

There are three different configurations included for the HLM strategy. A single HLV (configuration 1), an HLV in combination with one PSV (configuration 2) and an HLV in combination with two PSVs (configuration 3). For the breakdown maintenance it was found that the standalone HLV had the lowest energy demand, but the second configuration showed to be less costly and has a lower FOWT downtime. An exception to this is when the blade carrier is used, as this is a relatively expensive vessel. In the preventive maintenance campaign it was found that the single HLV is best suited in all aspects for the blade replacements. The HLV that is supported by one PSV does not provide any advantage compared to the other configurations. The HLV that is supported by two PSVs outperforms the other two configurations in cost. The energy demand of this configuration is in between the other two configurations. After analysis of the potential of the different fuels, it was found that LNG provides the most benefits in this strategy, without significant reductions in autonomy.

For the TTPM strategy different configurations were included. One AHTS vessel combined with one or two assisting AHTS vessels (configurations 4 and 5 respectively), or two AHTS vessels combined with two or four assisting AHTS vessels (configuration 6 and 7 respectively). Configuration 4 and 5 were compared for the breakdown maintenance. It was found that configuration 5 was preferred in terms of energy demand and FOWT downtime, but had a higher cost level. For the preventive maintenance it was found that configuration 7 is the most suitable in terms of energy demand and cost for the farm 10 km from shore. This switches to configuration 6 for the farms that are 50 and 100 km from shore. It must be noted that the large advantage compared to configuration 4 and 5 partially arises from excluding port idle time from the calculations. The alternative fuels; LNG, methanol and ammonia, showed to have great potential to reduce the green house gas (GHG) emissions.

Comparing the two strategies for breakdown maintenance, it was found that the HLM strategy has the lowest energy demand and FOWT downtime. However, the TTPM strategy performs better on the potentially important parameter cost. The TTPM strategy also shows to have slight advantages on preventive maintenance tasks, especially for the blade replacement campaign. However, this advantage relies strongly on the assumption that the O&M port has unlimited resources available at all times. Potential new innovations in the HLM and TTPM strategy showed to have a great positive influence on the cost and energy demand. An analysis was also performed on emission allowance legislation. This increases the cost of both strategies, but does not lead to a change in strategy. The emission allowance results in a stronger argument for the alternative fuel LNG.

In short, a calculation model was developed to compare O&M strategies on energy demand (GHG emissions), cost and FOWT downtime. It includes five vessel types which are used to compose seven configurations. The most sustainable (i.e. lowest energy demand) configuration for breakdown and preventive maintenance is the standalone HLV, except for full blade replacement campaigns. However, it does have a significantly higher cost level, which becomes decisive for the preventive maintenance strategy, making the TTPM strategy the better suited for preventive maintenance. New technological innovations were also included and showed to have great potential in the FOWT market. The model itself acts relatively sensitively on repair time and DP power demand. However, the assumptions on these parameters are equal for the different configurations, making it a useful tool to compare different configurations and new innovative concepts.

11

Recommendations

11.1. Introduction

For this study a calculation model was developed based on peer reviewed literature sources and empirical data. The model was verified and used for the comparison of two O&M strategies, which were covered in seven different support fleet configurations. Despite the best efforts, there still are topics of the calculation model and this research, which would benefit from further research. Some topics were already briefly discussed, but in this chapter a more detailed description will be provided on the recommendations for follow-up studies.

11.2. Include bunker time in calculations

It is recommended that bunker time is included in the calculation model. The time it takes to take in bunkers at the O&M port is currently set to 0 h. This means that as soon as a vessel visits port, its bunkers are set to fully filled. However, in practice this is certainly more than 0 h and differs a lot from port to port and the type of fuel which is taken in. This could potentially influence the overall in port time significantly as vessels either have to wait for their bunkers or bunker time itself is prolonged. Next to the operational time it could also potentially affect the downtime of a FOWT and the overall cost of the operations. Therefore, it is recommended to include the bunker time into the calculation model in further research.

11.3. Create seasonal weather timeline

The seasonal weather timeline is currently not included in the calculation model. One of the effects of the lack of seasonal changes is clearly demonstrated in the case study in chapter 6. The weather model is currently too stochastic, making it nearly impossible to simulate extended operations which require operational weather limits. Normally, the change of higher wind speed is greater during the winter months and lesser during the summer months. The inclusion of this seasonal pattern could indicate the potential benefit of performing operations in the summer months opposite to the more harsh winter months. The extended operation time could lead to extended FOWT downtime and increase in operational cost. Moreover, it could affect fuel consumption significantly if vessels have to wait standby in the field for a suitable weather window. In short, the effects of a correct weather timeline could change the results noteworthy and should therefore deserve a follow-up study.

11.4. Increase program runtime efficiency

Currently, the runtime of the calculation model is between 2 h and 3 h, which makes it impossible to apply the Monte Carlo method. During a Monte Carlo simulation the calculation model is run a large number of times to find any convergence on “variable” parameters, for example the vessel downtime. The increase in accuracy would certainly increase the confidence in the “variable” outcomes even further. This method is also used in other O&M models, which are used for the (floating) offshore wind industry. Therefore, it is recommended that research is conducted on how the calculation model can become more time efficient. One of the potential solutions could be the implementation of multithreaded programming, which allows for efficient parallel computing. In fact, it should become so efficient that the Monte Carlo becomes a possibility. The downtime of the vessels could potentially have effect on all analysis parameters of this report. Note that this only provides a real benefit if the seasonal weather timeline is included.

11.5. Include other floaters

In this report two types of floaters are included, the SPAR floater and the semi-submersible floater. Yet, there are two other floater types which are not covered in this research. These are the tension leg platform (TLP) floater and the barge floater. These floaters differ in surface area above water and underwater, which would result in a change of required bollard pull during the TTPM strategy. Another aspect that must be taken into account is the stability of the TLP floater during towage, as it is a mooring stabilised design. The HLM strategy on the other hand would not face any changes as it can operate independently of floater type. However, for the TTPM strategy it could be interesting to see what the actual effects of the different floaters are in terms of FOWT downtime, vessel cost and CO_{2eq} emissions. Therefore, it is recommended that TLP and barge floaters are designed and specified to support a 15 MW WT.

11.6. Validate when possible

It was already mentioned in chapter 6 that validation of the calculation model is currently not possible. Real life scenarios, combined with data collection, are needed to perform validation. However, up till now only a few FOWT farms were realised and data gathered during their operational lifetime are not publicly available. Nevertheless, the literature study showed that the FOWT market is growing rapidly, creating more potential for a validation study. The validation study could provide new insight in the accuracy and performance of the model.

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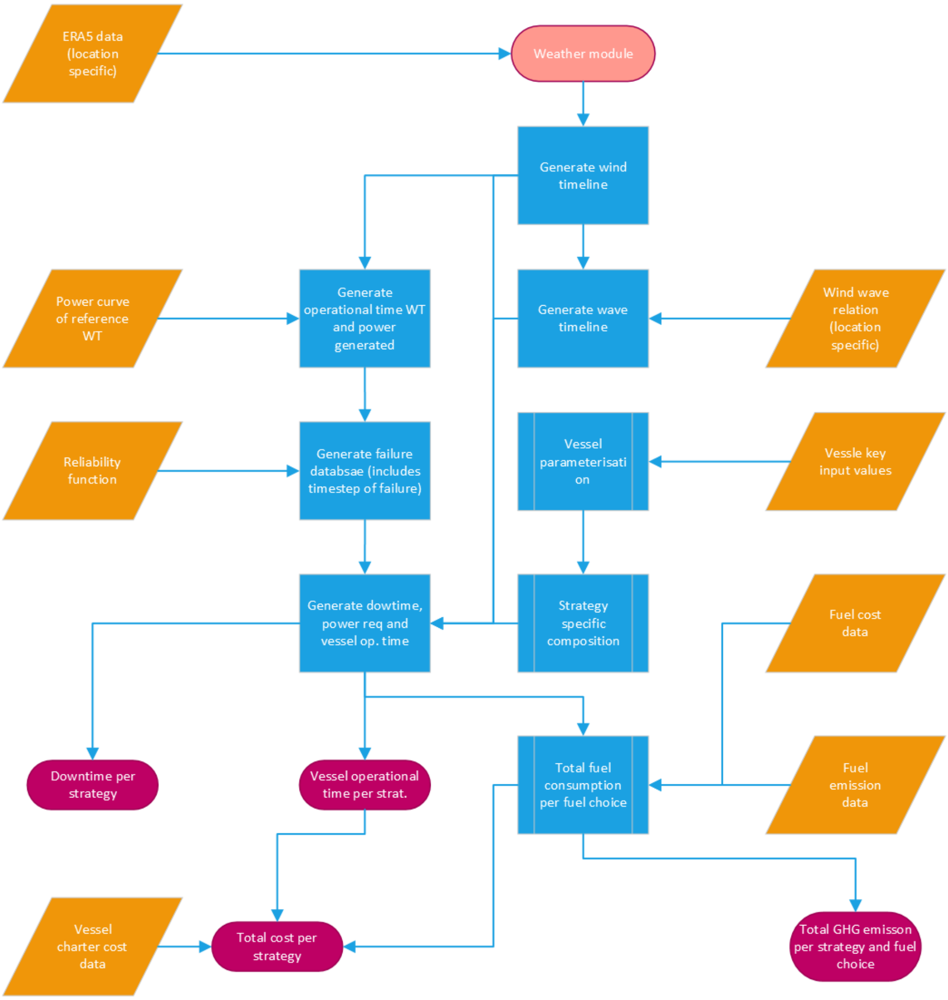
A

Model visualisation



B

Specifications 15 MW reference turbine

Table ES-1. Key Parameters for the IEA Wind 15-MW Turbine

Parameter	Units	Value
Power rating	MW	15
Turbine class	-	IEC Class 1B
Specific rating	W/m^2	332
Rotor orientation	-	Upwind
Number of blades	-	3
Control	-	Variable speed Collective pitch
Cut-in wind speed	m/s	3
Rated wind speed	m/s	10.59
Cut-out wind speed	m/s	25
Design tip-speed ratio	-	9 0
Minimum rotor speed	rpm	5.0
Maximum rotor speed	rpm	7.56
Maximum tip speed	m/s	95
Rotor diameter	m	240
Airfoil series	-	FFA-W3
Hub height	m	150
Hub diameter	m	7.94
Hub overhang	m	11.35
Rotor precone angle	deg	-4.0
Blade prebend	m	4
Blade mass	t	65
Drivetrain	-	Direct drive
Shaft tilt angle	deg	6
Rotor nacelle assembly mass	t	1,017
Transition piece height	m	15
Monopile embedment depth	m	45
Monopile base diameter	m	10
Tower mass	t	860
Monopile mass	t	1,318

deg	degrees	rpm	revolutions per minute
m	meters	t	metric tons
m/s	meters per second	W/m^2	watts per square meter

C
FOWT concepts

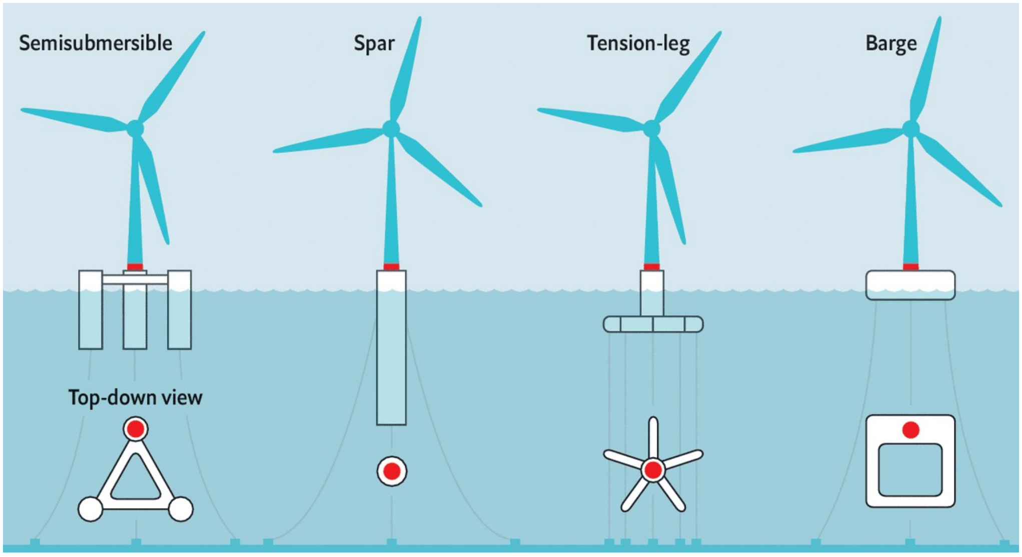


Figure C.1: Floating offshore wind turbine concepts [60]

C.1. Barge

The barge concept is a metal or concrete shaped ring or square as seen from the top. Due to this shape a damping pool is created in the middle, which dampens the motions of the floater. The WT is often installed on the ring. The concept can be anchored by either drag embedded anchors or suction anchors [14]. The barge floater is buoyancy stabilised, making it better suited for wet towage compared to the ballast or mooring stabilised floaters. This makes them suitable floaters for in port assembly and decommissioning [11]. Also large maintenance can be performed in port, making it a suitable candidate for the tow to port O&M strategy.

C.2. Semi-submersible

The semi-submersible floaters are typically made from three or four upright cylindrical floaters which are connected at some distance from each other by a frame. This makes that they have a relatively large waterplane area compared to the other floater types. This large waterplane in combination with active or passive water ballast and large damping plates under the cylindrical floaters is used to gain stability [14]. The WT is often placed on one of the cylindrical floaters [31]. The other floater can be fitted with a helipad or other components [11]. This type of floater is also buoyancy stabilised and shares the same advantage as the barge type floater. Semi-submersible floaters are best used at water depths greater than 50m and are considered to have the highest TRL compared to other floater designs [31].

C.3. Single point anchor reservoir

The single point anchor reservoir or SPAR concept, in contrast to the semi-submersible floater, uses only one upright cylinder. Upon this cylinder the WT is installed. This type of floater has the greatest draught which can be up to 100 metres, limiting the possibilities for in port operations. Assembly, large maintenance and decommissioning should therefore be conducted in sheltered coastal areas [11]. This draught also forced the concept to be more suitable for deeper waters, starting around a depth of 100 metres.

In case of the Hywind Scotland project the floaters were brought to a sheltered area where they were brought in upright position by water ballast. This ballast was then replaced by solid ballast. Then the complete WT was placed on the floater by a HLV [11].

Despite this floater type being ballast stabilised it can still be wet towed. However, this comes with the notice that the weather window for towage is smaller compared to the buoyancy stabilised floater. The smaller weather window and requirement of expensive HLVs gives this floater type a lower TRL compared to the semi-submersible floater. [31].

C.4. Tension leg platform

The tension leg platform or TLP also originates from the oil and gas industry, just like the SPAR concept. It uses tendons or steel wires on the corners of its submerged base. This concept is far lighter than the other concepts and many varieties on TLP floaters have been developed. The TLP can be wet towed to location after in port assembly, but caution is advised during this operation. The TLP is a mooring stabilised concept, meaning the floater is less stable when it is not connected to its mooring system. Additionally, difficult mooring disconnection makes the TLP concept less suitable for the tow to port strategy for maintenance activities [11]. Despite many varieties having been developed, only a few scaled prototypes have been reported, thereby leading to the lowest TRL of the discussed concepts. It is recommended to use the TLP at water depths of at least 80 metres to grant the mooring cables or tendons their necessary length [31].

D

Floater dimensions for reference turbine

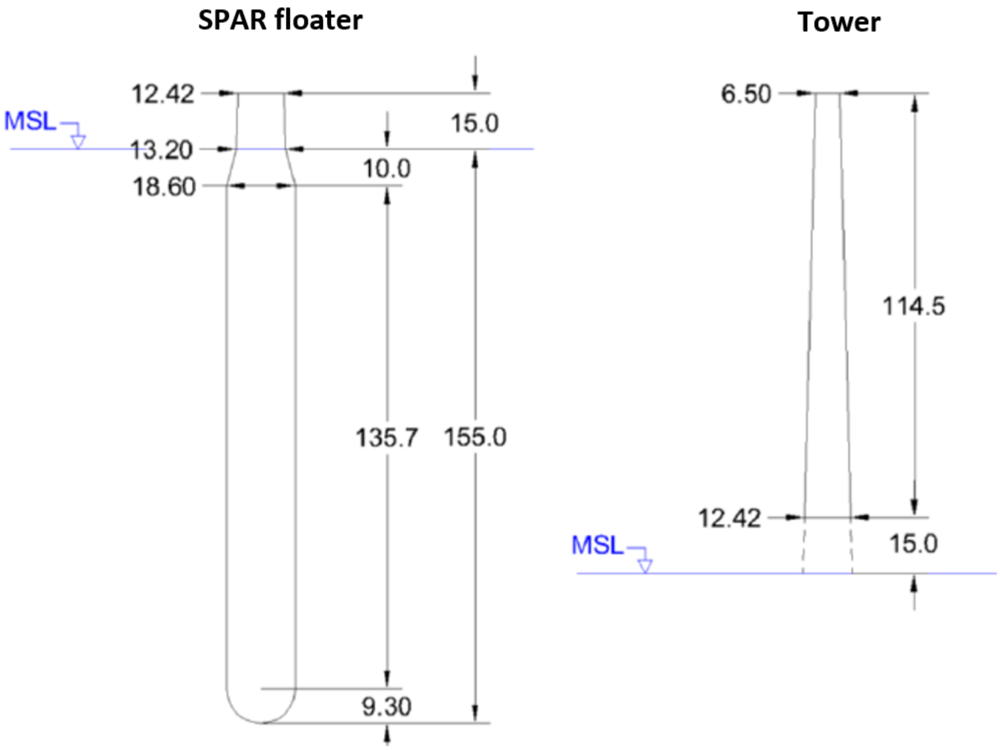


Figure D.1: Dimensions of SPAR floater for the 15 MW reference wind turbine [3].

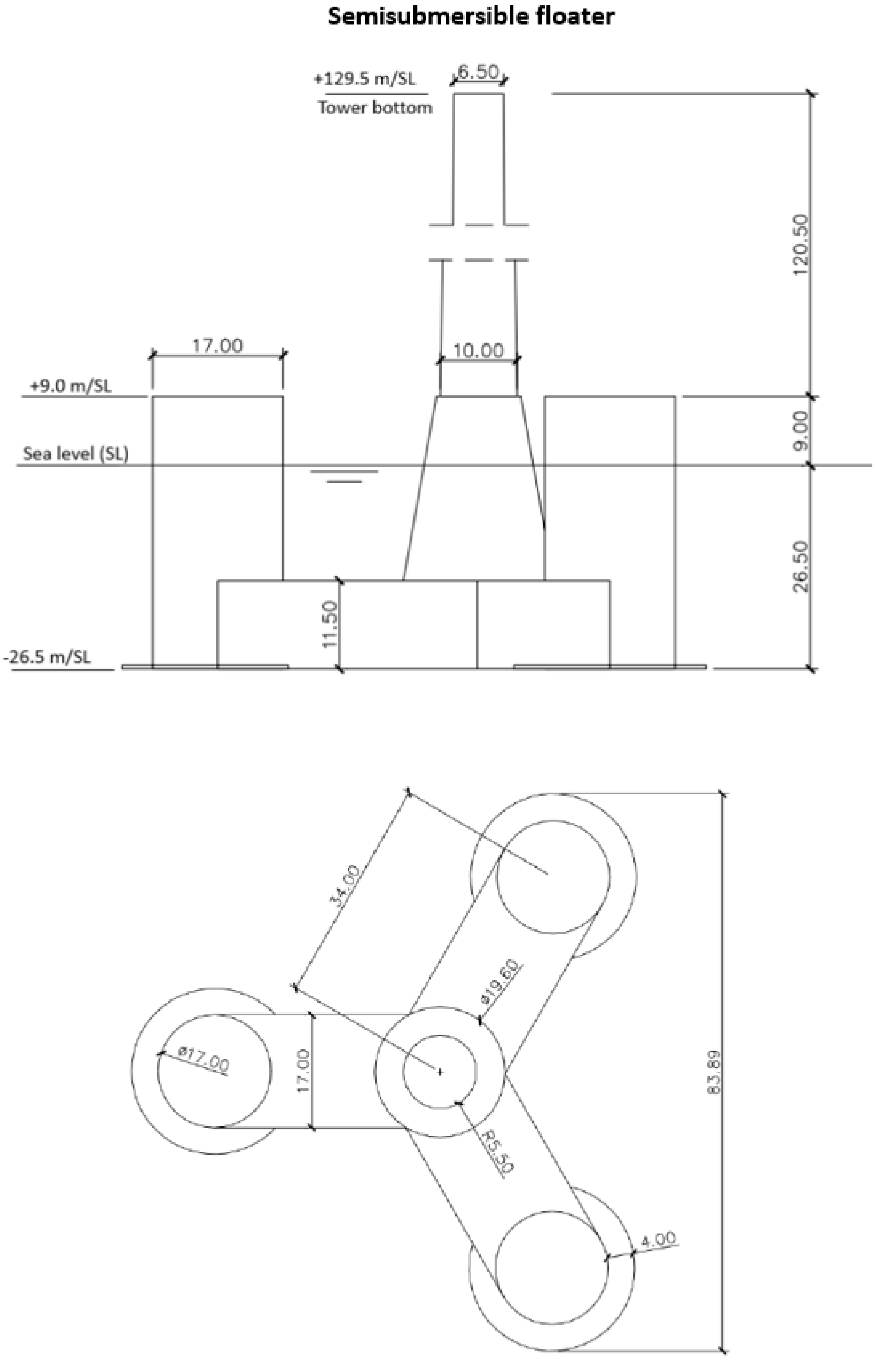
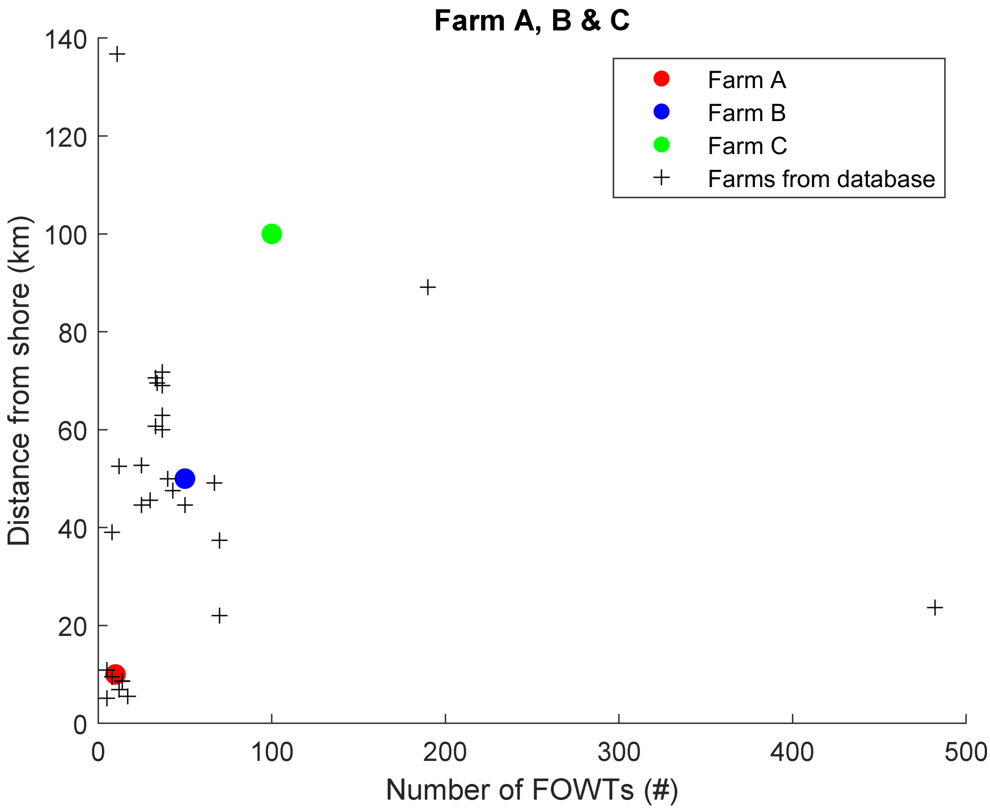


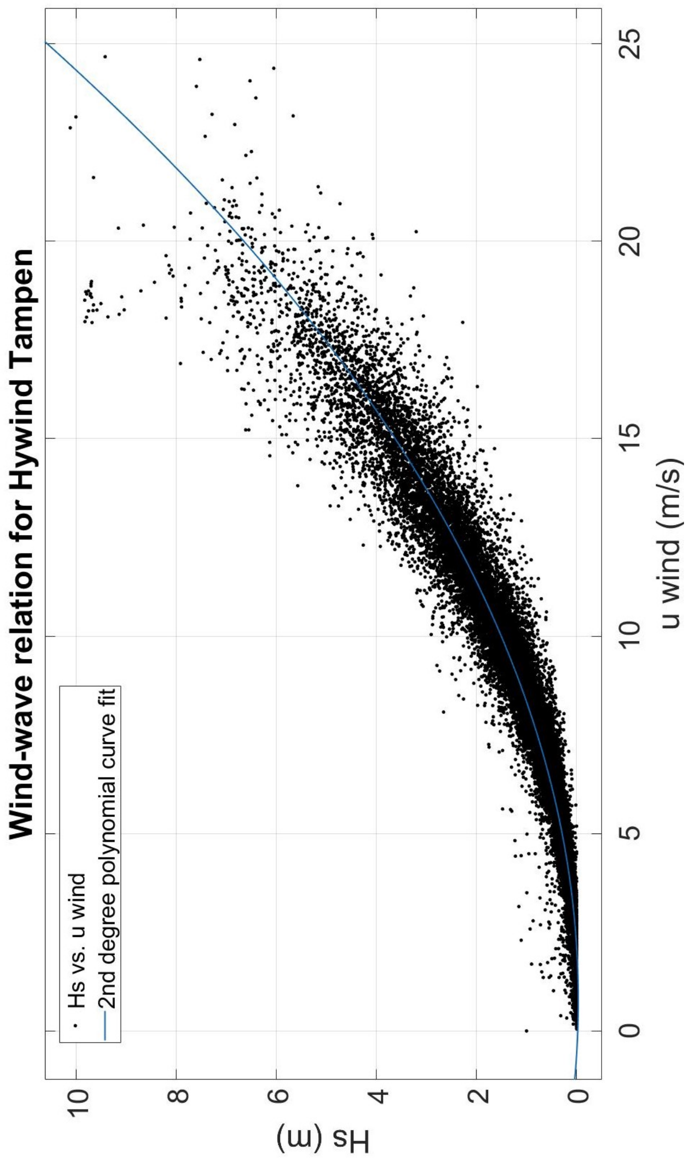
Figure D.2: Dimensions of semi-submersible floater for the 15 MW reference wind turbine [3].

E

Scatter diagram

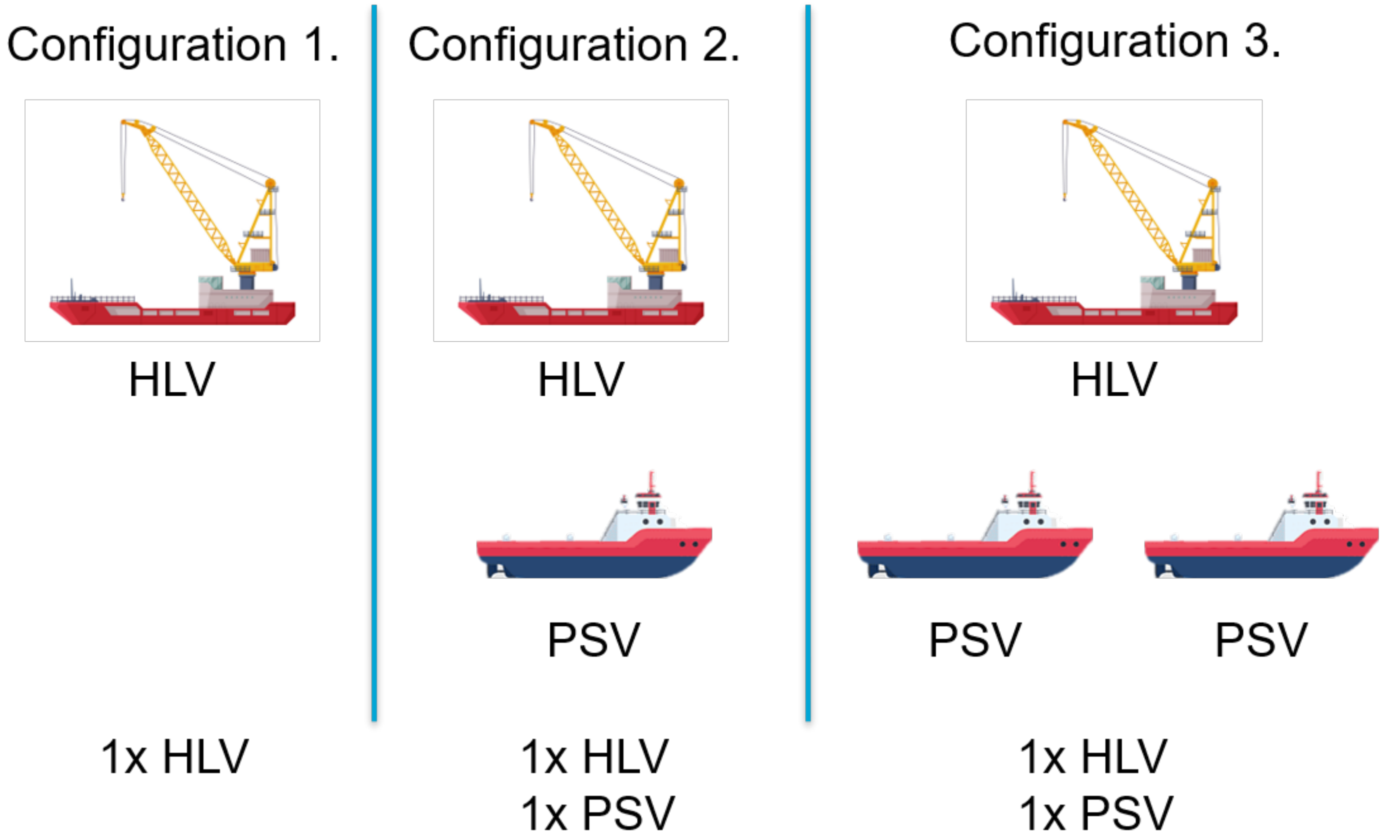


F
Example wind-wave relation

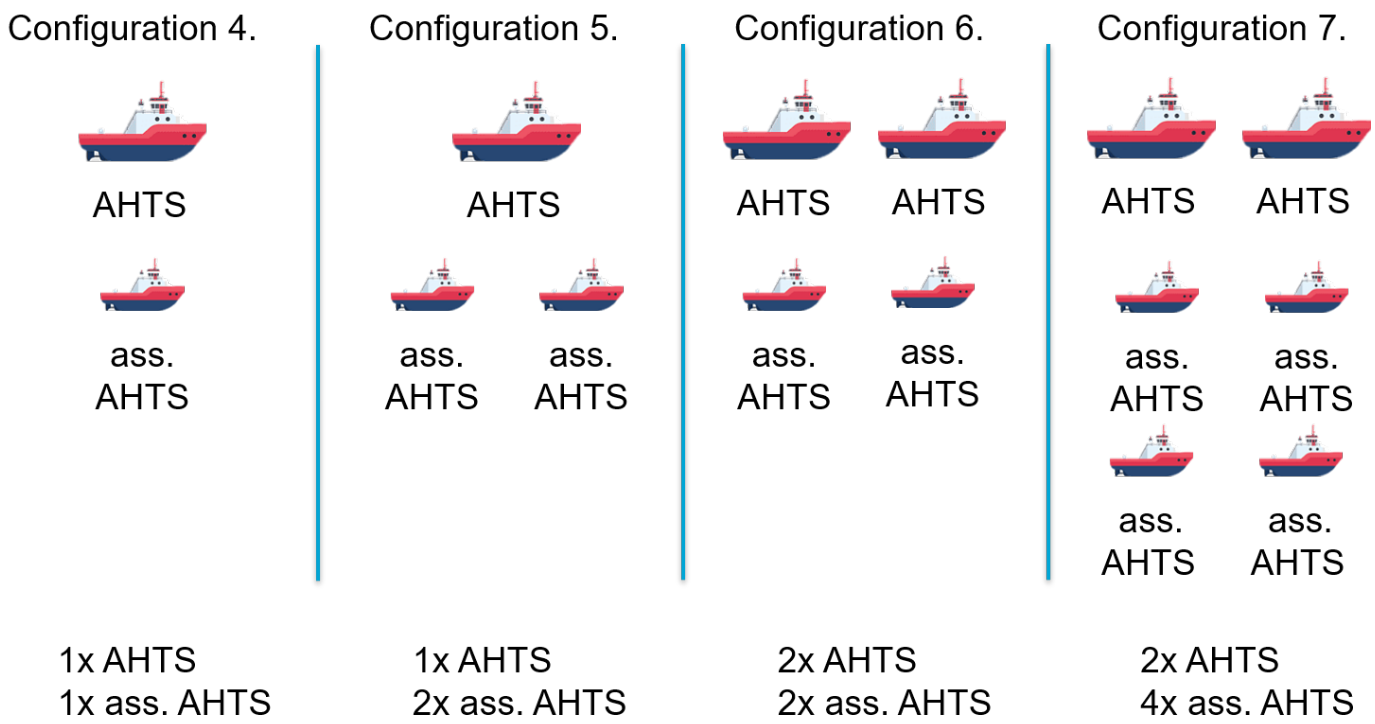


G

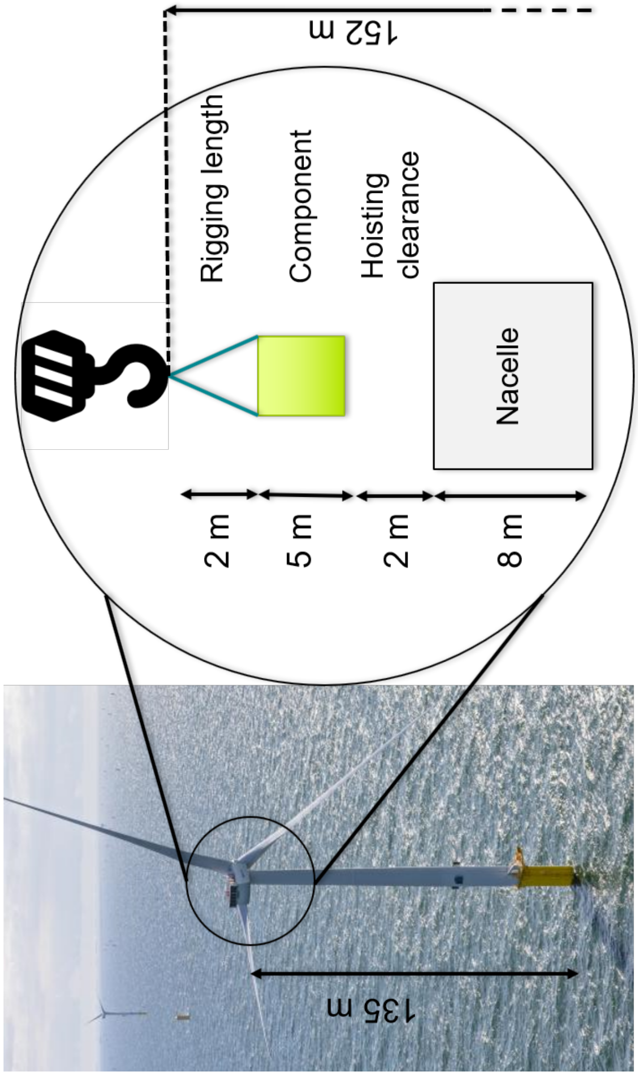
HLM support fleet configurations



TTPM support fleet configurations



Estimation on lifting height

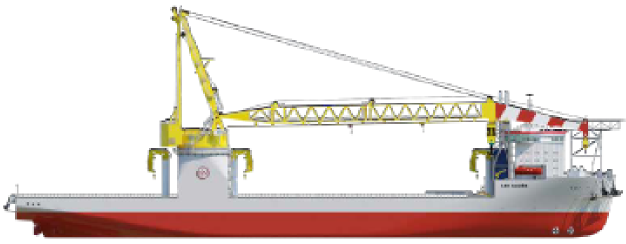


J

Specifications HLV Les Alizés

Les Alizés.

Les Alizés.



DP2 Heavy Lift Crane Vessel

Classification	Offshore Construction Vessel - Lifting DYNAPOS-AM/AT-R (DP Class 2) Unrestricted navigation Clean Ship ND07 - Green passport EU
Flag	Luxembourg
Length Overall	236.8 m
Breadth	52 m
Maximum Draft	10.5 m
Moulded Depth	16 m
DWT	61,000 t

CRANE SYSTEM

Crane Make	Huisman
Max. Lifting Capacity	Main block 5,000 t at 36 m
Auxiliary Block	1,500 t at 46 m
Lift above Deck	Main block: 125 m at 21.5 m Auxiliary block 167 m at 29.5 m
Depth Range	Auxiliary block 600 t at 100 m water depth Auxiliary block 380 t at 440 m water depth
Cargo Deck	9,300 m²
Max. Deck Load:	30t/m²

MACHINERY - PROPULSION

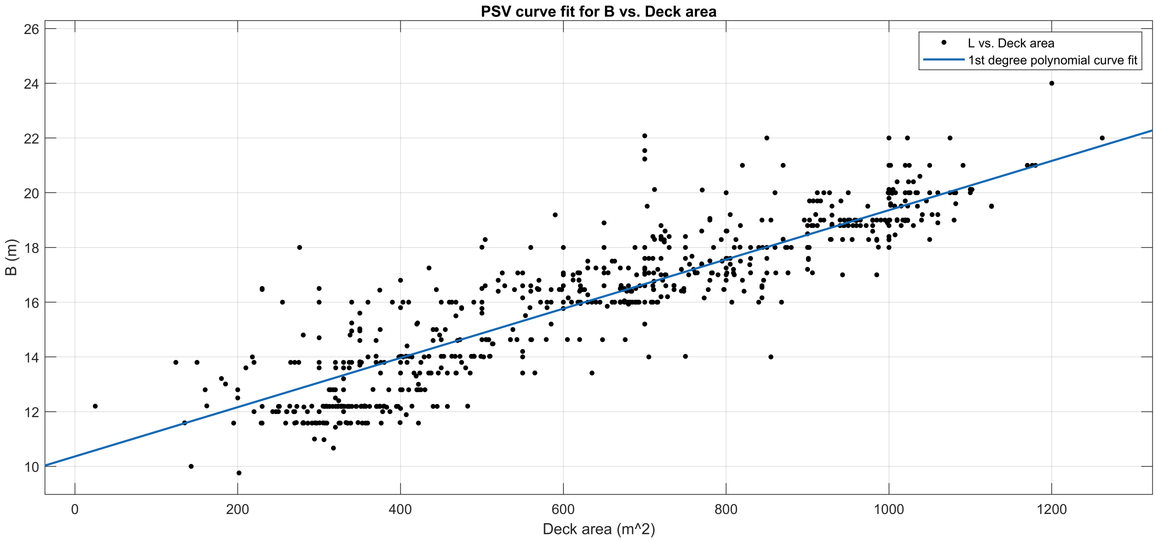
Main Gen. Sets	Diesel Engines MAN 6 x 7,200 kW 3 x 6,600 V, 60 Hz
Emergency Gen. Set	600 kW
Harbour Gen. Set	1,700 kW
Emissions	ULEv (Ultra Low Emission vessel) IMO Tier III Euro stage V Inland Waterway (using DPF)
Main Propulsion	4 x azimuth thrusters 3,000 kW
Retractable Thrusters	2 x 3,250 kW
Bow Thrusters	2 x 2,600 kW
Max. Speed	13 kn

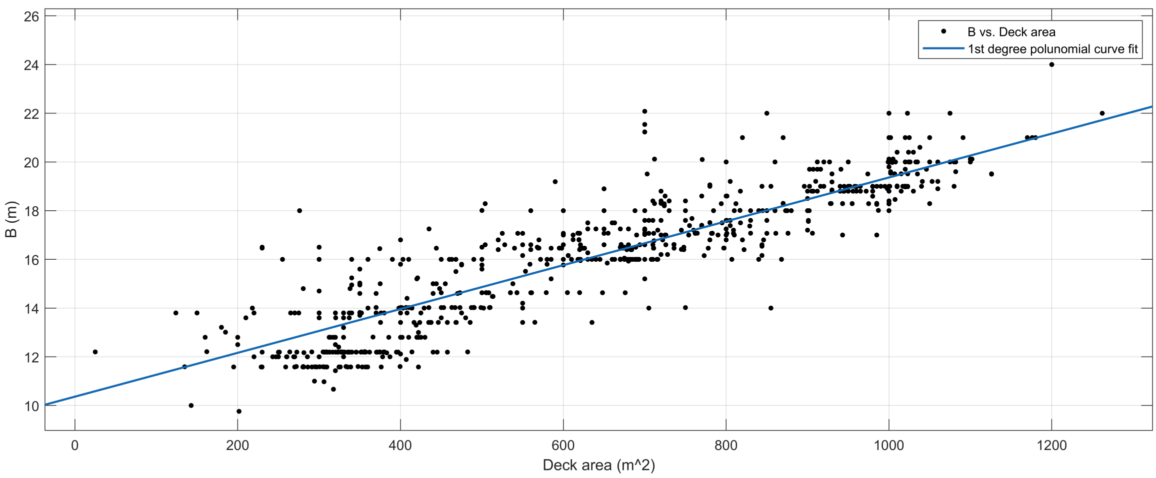
ACCOMMODATION

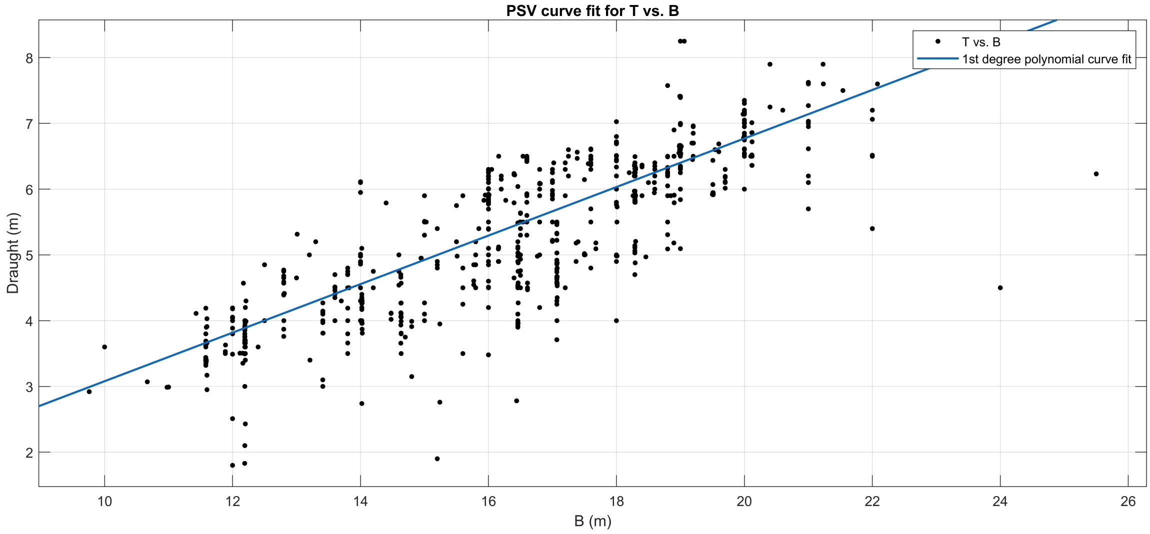
Accommodation	120 single, 15 double cabins
Heli Deck	D 22.8 m, MTOW 14.6 t, Sikorsky S-61N, S-92 and Agusta-Westland EH-101

K

Curve fits for PSV parameterisation






PSV curve fit for T vs. B
T vs. B
1st degree polynomial curve fit
Draught (m)
B (m)
2
3
4
5
6
7
8
10
12
14
16
18
20
22
24
26

L

Bollard pull calculation

L.1. Calculation concept

BP is the strength at which a vessel can pull a floating object. In this case a FOWT will be towed through the water. It is important to specify which extreme environmental conditions are to be expected, because this will set the minimum holding force. The holding force is the force required to keep the floating object in position, when including the environmental forces. DNVGL Guidelines for Marine Transportation has described standard wind, wave and current parameters, which can be used for towing operations. These standards are either for ”open ocean tows” or ”benign weather areas”. From a conservative standpoint it is decided that the ”open ocean tows” standard will be used, as described in table L.1. This is the first step in the BP calculations and is followed by determining the transverse area of the FOWT.

Table L.1: Open ocean tow standards.

Wind speed	20.0	m/s
Current speed	0.5	m/s
Significant wave height	5.0	m

L.2. Wind turbine assumptions

To determine the wind forces it is necessary to determine the transverse windage area, also referred to as the transverse wind-exposed sectional area. In order to calculate this area a number of assumptions have to be made, with regards to the WT. These assumptions are based on the NREL report on the reference wind turbine and visualised in figure L.1 and L.2.

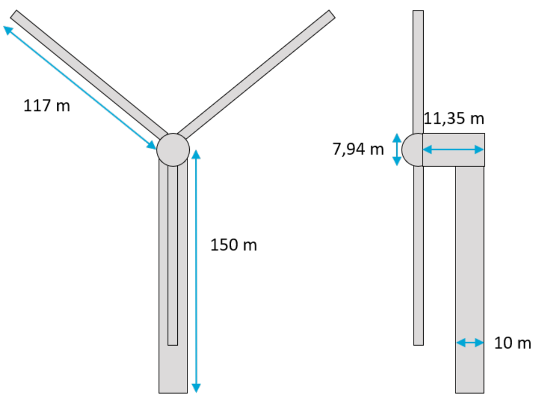


Figure L.1: WT assumptions.

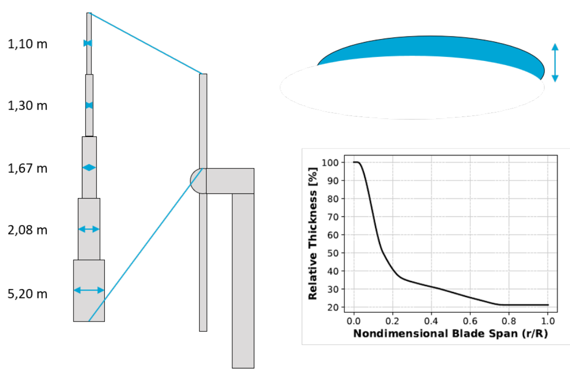


Figure L.2: WT blade assumptions.

Areas of the WT are calculated according to equation L.1, where the L is the length of the area and B the width. The shape factor C_S is a potential deduction or addition of resistance area. Several options have been calculated and it was found that the lowest windage area exists when the WT hub and rotor face to the aft. The tower itself is cylindrical, thus a shape factor of 0.5 is implemented. The blades have the same shape coefficient and are assumed to be in vane position when transported. In figure L.1 the blue arrows in the top right mark the area that will face the tug. The blade tapers to the end of the blade according to the diagram shown in figure L.2. On the basis of this graph the estimation is made for the rate at which the blade tapers and is shown on the left side of figure L.2. The nacelle is assumed to be 7.94 m x 7.49 m, which is equal to the outer hub diameter. In total the windage area is 966m^2, when the shape factors are included.

$$A_{windage} = L \cdot B \cdot C_S \tag{L.1}$$

L.3. Floater assumptions

The floaters face both current and wind forces. Therefore, two different calculations have to be performed for the two floaters considered in this research.

L.3.1. SPAR floater

The SPAR floater only has a small fraction of its structure above the water. This part is on average 15 m high and 12.8 m wide and is also assumed to have a cylindrical shape. Equation L.1 can again be used to determine the windage area, which is 6.4 m^2.

The underwater area that interacts with the current is also assumed to be cylindrical and is about 18.6 m x 155 m. For the current area also a shape factor is in place, which is equal to the shape factors used for the windage area. With the use of equation L.1 it is found that the total current area is 1441.5 m^2.

L.3.2. Semi-submersible floater

The semi-submersible floater has a larger windage area compared to the SPAR floater. There are three cylindrical tubes, which rise 9 m above mean sea level and have a diameter of 17 m. Per cylinder this leads to a windage area of 76.5m^2, which is 230 m^2 for the three floaters combined.

The semi-submersible floater has a smaller underwater area than the SPAR floater. The three cylinders that rise above the water continue underwater and are connected with a frame. It is assumed that the frame, which connects the cylinders, has a flat surface. Therefore, the shape factor is set to 1 for this part of the floater. The combined underwater area, with inclusion of the shape factors, is found to be 961 m^2.

L.4. Environmental forces

There are in total three different environmental forces at play when towing a FOWT from or to the site. These are the wind forces, wave forces and current forces.

L.4.1. Wind force

The wind force (F$_{wind}$) can be calculated with equation L.2, where ρ_{air} is assumed to be 1.225 kg/m^3. The wind force (u$_{wind}$) comes from table L.1 and is set at 20 m/s. The windage area (A$_{wind}$) was calculated in the previous sections for both floater types.
The SPAR floater faces a maximum wind force, at harsh open ocean conditions, of 237 kN, whereas the semi-submersible floater faces 255 kN. This shows that the larger windage area increases the wind force significantly.

$$F_{wind} = \frac{1}{2} \cdot \rho_{air} \cdot u_{wind}^2 \cdot A_{wind} \tag{L.2}$$

L.4.2. Current force

The other environmental force is the current force, which can be calculated with the use of equation L.3. Note that equation L.3 is similar to equation L.2, as both calculate a force from fluid interaction. However, for the applied current force the density of seawater ($\rho_{seawater}$) is used, together wind the current speed

($u_{current}$). The density of seawater is assumed to be 1025 kg.m^3 and the current speed is shown in table L.1. The underwater area that interacts with the current ($A_{current}$) was already determined in the previous section.
The current force is calculated to be 185 kN for SPAR and 123 kN for semi-submersible. Note that, again, the large area that interacts with the fluid leads to a significant increase in applied force.

$$F_{current} = \frac{1}{2} \cdot \rho_{seawater} \cdot u_{current}^2 \cdot A_{current} \tag{L.3}$$

L.4.3. Wave drift force

The last environmental force is the added wave resistance or the wave drift force (F_{wave}) and is calculated according to equation L.4. This wave drift force is related to the significant wave height (H_s) and width of the floater (B). Moreover, it can get an addition or deduction factor for the shape a wave encounters. For both floaters the shape form is cylindrical. However, the shape factor (R) for the wave drift force is 0.88, instead of 0.5, which was found for the underwater and wind area.
It is found that the wave drift force is a dominant force for the semi-submersible floater at 1241 kN, due to its large surface piercing width. The SPAR floater only meets 453 kN of force, due to the waves.

$$F_{wave} = \frac{1}{8} \cdot \rho_{water} \cdot g \cdot R^2 \cdot B \cdot H_S^2 \tag{L.4}$$

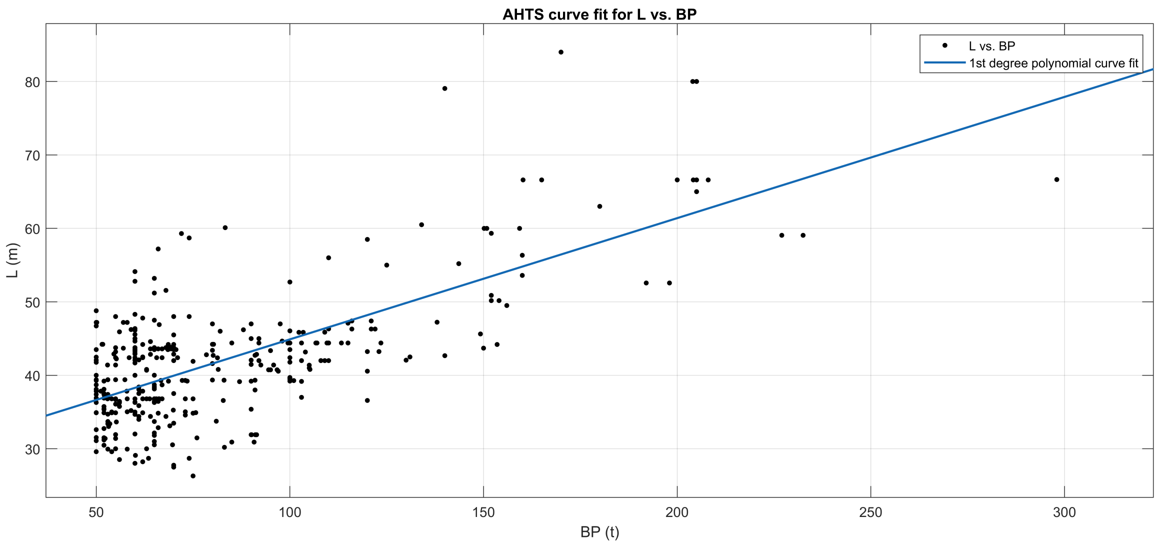
L.4.4. Total force and bollard pull

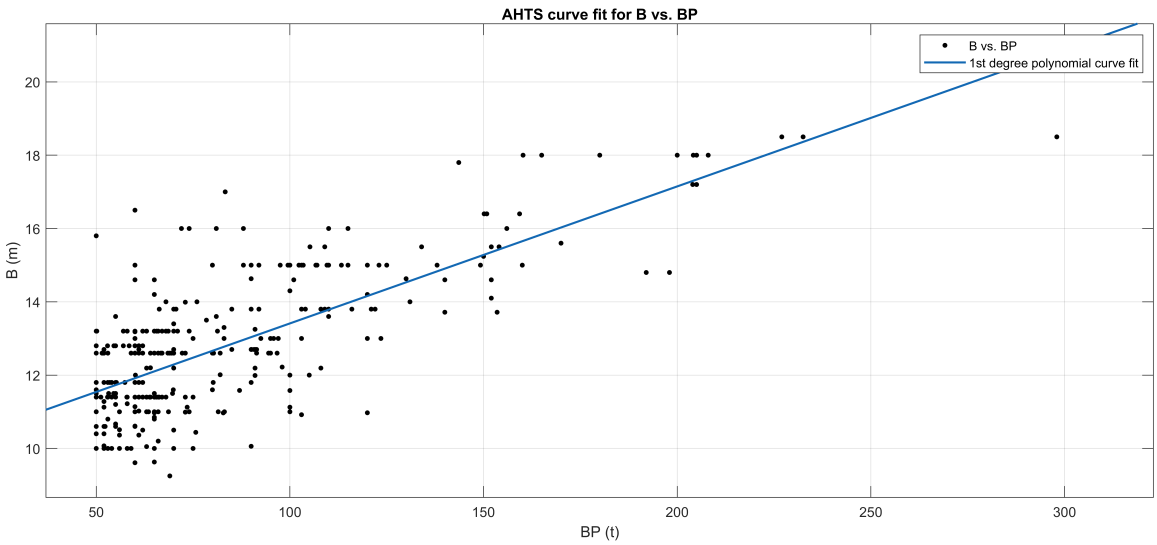
The total force (F_{tot}) required to keep the FOWT in holding position in harsh open ocean conditions is the addition of the three environmental forces. This is dived by the correction factor (η_t), which is the tug efficiency. This efficiency is assumed to be 0.75, which is derived from the ND-0030 Guidelines for Marine Transportation. The total BP required for the SPAR and semi-submersible floater is calculated according equation L.5 and was found to be $\pm$ 120 t and 220 t respectively.

$$BP = \frac{F_{tot}}{g \cdot \eta_t} \tag{L.5}$$

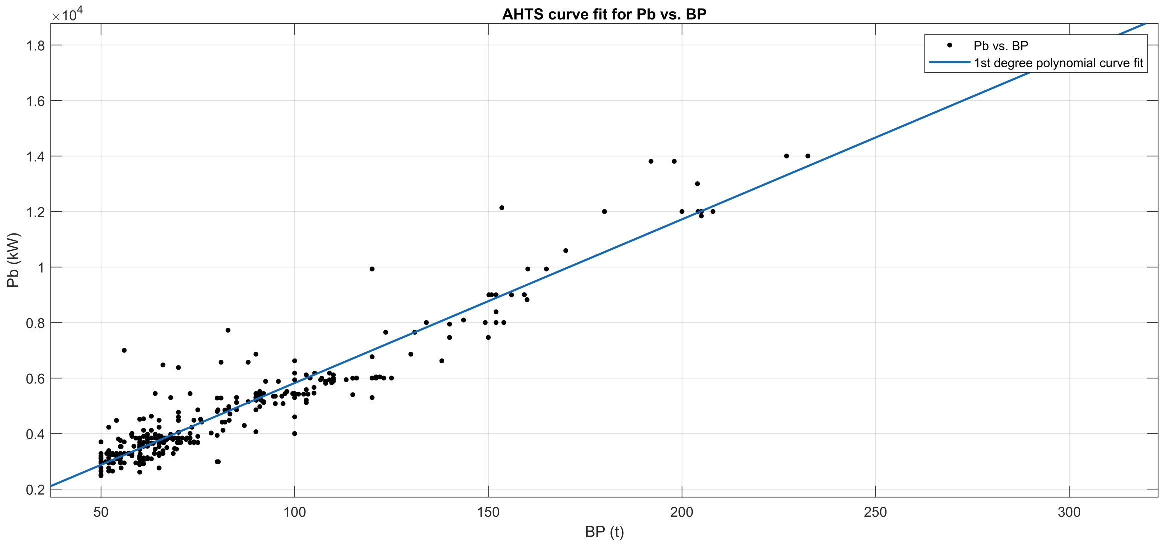
M

Curve fits for AHTS parameterisation




AHTS curve fit for B vs. BP
B vs. BP
1st degree polynomial curve fit
B (m)
BP (t)
10
12
14
16
18
20
50
100
150
200
250
300


AHTS curve fit for T vs. BP
T vs. PB
1st degree polynomial curve fit
T (m)
BP (t)
3
4
5
6
7
8
50
100
150
200
250
300


AHTS curve fit for Pb vs. BP
×10^4
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
Pb (kW)
50
100
150
200
250
300
BP (t)
Pb vs. BP
1st degree polynomial curve fit

N

Failure data set

Timestamp	WT ID	component
1642	9	gearbox
7364	4	generator
11237	11	generator
12398	4	gearbox
15252	8	generator
20556	3	gearbox
31920	5	generator
32263	9	gearbox
36053	11	gearbox
42796	2	generator
43816	4	gearbox
43998	4	generator
45019	6	generator
45855	6	generator
46821	6	generator
49744	10	gearbox
49787	8	gearbox
62773	3	gearbox
62785	7	gearbox
64746	4	generator
73276	3	generator
77974	2	gearbox
94963	8	gearbox
97986	7	generator
103379	7	gearbox
105928	4	gearbox
106146	10	gearbox
112582	6	gearbox
112722	3	generator
113497	5	generator
114345	9	gearbox

Timestamp	WT ID	component
115579	10	gearbox
116300	11	generator
126790	11	generator
129175	3	generator
132605	4	gearbox
132978	2	gearbox
138403	4	generator
139814	9	gearbox
144779	8	generator
144950	11	gearbox
146152	6	gearbox
146250	7	generator
147787	7	generator
147808	9	gearbox
148330	6	generator
158836	2	gearbox
159086	4	generator
160244	6	gearbox
166075	9	gearbox
167412	10	generator
168598	2	gearbox
171702	7	gearbox
177406	6	generator
178894	9	generator
188161	4	generator
212895	2	generator
215141	5	generator
215423	6	gearbox
215822	5	gearbox
216228	9	gearbox