Routing and scheduling of maintenance support vessels for an offshore wind and solar farm

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Routing and scheduling of maintenance support vessels for an offshore wind and solar farm

by

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Preface

Floating photovoltaic (FPV) is an emerging concept. Potential is recognized in combining FPV and offshore wind farms to create an offshore wind and solar farm. One of the remaining uncertainties around the potential of an offshore wind and solar farm is the value of the operations and maintenance cost. As one of the main contributing factors to operations and maintenance costs of offshore wind farms is the accessibility, integration of the transport for maintenance of the wind turbines and solar units can minimize the costs. By means of a route and scheduling optimization tool the optimal route and schedule of maintenance support vessels for a virtual OWSF is investigated. The research indicates that the optimal route and schedule of maintenance support vessels for a virtual OWSF does not include integration of the transport. The main reason is the low costs of an RHIB compared to the cost of a CTV or SOV. However, the optimal route and schedule is very case dependent. Thus recommended is to apply the model to multiple case studies to form a general conclusion.

I would like to thank my supervisors Iana Bakhmet for including me in this interesting topic and the guidance during the process even after the internship had ended. Furthermore, I would like to thank Xioali Jiang for her guidance to help deliver a sufficient academic report.

J.H. Hablé
Delft, 16th of June 2022

Summary

There is an increasing interest in combining solar and wind energy harnessing offshore. By combining the solar and wind energy generation offshore an increased power output per unit surface area and a reduction in the temporal variability of the output would be realised compared to non-hybrid energy harnessing farms. In addition, the electricity infrastructure can be combined for the wind and solar facilities, thereby reduce construction costs.[1]

Problem description

One of the remaining uncertainties around the feasibility of an offshore wind and solar farm (OSWF) is the operations and maintenance (O&M) cost [2]. The main challenge in O&M of offshore installations is the accessibility. Small weather windows due to the combination of bad weather conditions and regulations, especially safety regulations, decrease accessibility and therefore decrease the availability of the wind farm [3]. O&M support strategies are being investigated for offshore wind farms that make better use of the weather windows and vessel transfers possible [4][5]. The largest part of O&M support for offshore wind farms is the logistic operation for the maintenance tasks [4]. Therefore, this research focuses on the logistic aspect of the maintenance operation i.e. the offshore maintenance support. The objective is to develop an optimal route and schedule of the maintenance support vessels for an OWSF. It is expected that combining the offshore logistics of the wind and solar maintenance tasks will be advantageous because of the high cost of the operation and small time windows due to weather conditions. Combining the maintenance support has the potential to increase the effective use of the time windows and the vessel transfers.

Method

Literature study is conducted to determine the requirements for developing an optimal route and schedule for maintenance support vessels of an OWSF. An optimization model existing of a mathematical model and a solution method is required. The requirements that the model must meet to be applicable for an OWSF are: Maintenance tasks are allocated to different nodes; Multiple vessels are included with different routes; Different characteristics for vessels; Multiple service orders per tour; Downtime costs are related to weather conditions; There is a distinction between preventive and corrective maintenance tasks. The different mathematical formulations in the literature for offshore wind farms are assessed on which requirements for an OWSF are included. The mathematical problem formulated in the research of Raknes et al. [6] includes most of the requirements for representing the maintenance support vessel routing and scheduling problem for OWSFs. The solution methods from studies that developed an optimization model for maintenance support vessel routing and scheduling of offshore wind farms are evaluated on computational time and accuracy of the solution, the applicability for different mathematical formulations of a routing and scheduling problem. The commercial solver Gurobi is selected as solution method. The mathematical problem formulation of Raknes et al. is adjusted to be fully applicable for an OWSF. The implemented adjustments are: The nodes represent the wind turbines and solar units instead of wind farms; The vessels are enabled to visit multiple nodes during one shift; A set of RHIBs is added.

Case study

The OWSF model is applied to a case study in order to find the optimal route and schedule of maintenance support vessels for an OWSF. At the moment no offshore wind and solar farm are in operation. Therefore, an virtual OWSF is created based on an operating offshore wind farm. The Prinses Amaliawindpark (PWAP) in the Dutch North Sea is taken as base for the case study. The wind farm is in operation since 2008. It is located 23 km from its maintenance port IJmuiden and contains 60 2 MW

turbines. The virtual OWSF contains 6 wind turbines and 2 solar units with a relative between them based on the average distance between wind turbines in the PAWP. The case study analysis Two scenarios; in May and in February. May is a month with low wind speeds. Therefore, regular preventive maintenance of offshore wind turbines is often performed in May. February is a month with high wind speeds. The weather conditions result in limited weather windows for maintenance. Therefore, it is assumed that only corrective maintenance is performed in February. Accordingly, the required maintenance is determined for the two scenarios. The data and information required for the wind turbines and solar units is extracted from an ongoing research at TNO. The weather conditions are determined from the weather data of the Prinses Amaliawindpark in 2014. This data does not include solar radiation data. Therefore, average estimated solar radiation at the Dutch North Sea is used. The two scenarios consists of the first 4 shifts of the month and include 3 CTVs, 1 SOV, and 1 RHIB.

The case study shows that the optimal route and schedule of maintenance support vessels for an OWSF includes no integration between the support for the maintenance of the wind turbines and for the solar units. The maintenance of the solar units is performed with separate transport than the maintenance of the wind turbines.

Conclusion

This research aims to develop an optimal route and schedule of the maintenance support vessels for an OWSF. The main research question is *What is the optimal route and schedule of maintenance support vessels for an offshore integrated wind and solar farm?* The results of the case study show that the optimal route and schedule of maintenance support vessels of an OWSF includes separate trips to the turbines and solar units. This result indicates that integrating the maintenance support for offshore wind turbines and offshore floating solar does not decrease the travel and downtime costs. This is mainly because the use of an RHIB is much cheaper than the use of a CTV or SOV.

Recommendations

For further research it is recommended to analyse different scenario's and extent the range of required maintenance tasks to determine whether integrating the maintenance support for offshore wind turbines and offshore floating solar will decrease the travel and downtime costs. Furthermore, the accuracy of the case study can be increased by including the availability of spare parts, technicians, equipment. For further elaboration of a case study the type of contracts for the vessel use that are in place should be considered as it affects the development of a cost optimal schedule. When further developing the OWSF model, implementing a heuristic solution method is recommended to decrease the computational time and research is needed to reduce the required memory for running the model. Lastly, in order to determine whether the route and schedule developed by means of the OWSF model is optimal, it should be applied to an operational OWSF.

Contents

Nomenclature

ACO Ant Colony Optimization

ALNS Adaptive Large Neighborhood Search

AS Ant system

ATB aggregate time block

AV Accommodation vessel

DTB detailed time block

DWPS Discrete wolf pack search

FPV Floating photo voltaic

GA Genetic algorithm

MIP Mixed Integer Programming

MPSO mixed particle swarm optimization

MSE Mean Square Error

O&M Operations and maintenance

O&M Operations and maintenance

OWSF Offshore wind and solar farm

PSO particle swarm optimization

TARP Technician Allocation and Routing Problem

TSP Traveling Salesman Problem

VRP Vehicle Routing Problem

VRPDP Vehicle Routing Problem with Pick-up and Delivery

WRRP workover rig routing problem

1 Introduction

The Paris Agreement, signed by 194 states and the European Union, has the purpose to limit the temperature increase in response to the global climate change threat. In order to limit the global warming, countries aim to reach global peaking of greenhouse gas emissions as soon as possible [7]. The ongoing energy transition is one of the efforts to limit the greenhouse gas emission. It induces a shift from carbon-based to renewable sources for energy generation. According to Rosa-Clot and Tina [8] multiple analysis are performed to predict the continuation of the energy transition. They all converge to a few concepts including the expectation that renewable energy sources will provide 80% of the full electric energy production with solar and wind sources both leading in the electric energy production. A drawback of wind and solar energy harnessing is the irregularity of the sources which complicates the grid integration. Another important drawback is the amount of area needed to meet the electricity demand. The average power density of solar and wind technologies (7 W/m^2 and 3 W/m^2 resp.) are much lower than the average energy density of non-renewable energy generation technologies (307 W/m^2)(see figure 1.1) [9].

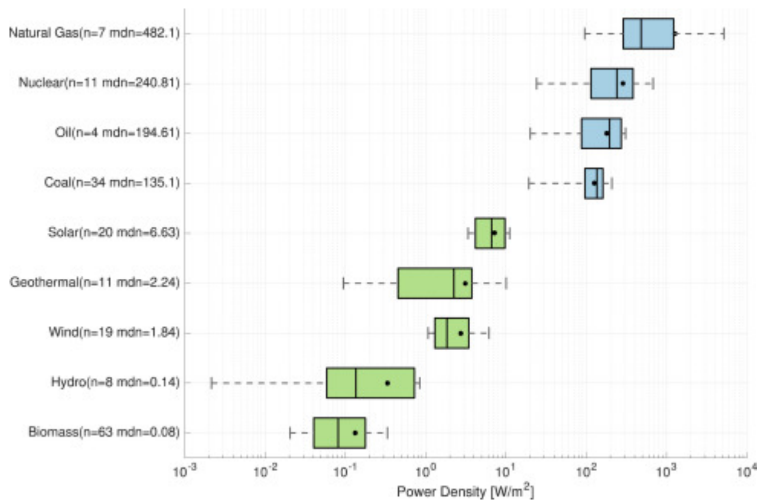


Figure 1.1: Box plots of power densities for all energy types visualized on a log scale. The annotations n and mdn give the number of values found for each energy type, and the median power density respectively. Outliers are those values that are further away than 0.5 and 1.5 times the 1st and 3rd quartiles respectively. The round markers show the mean for each energy type. Green boxes are given for renewable energy types, and blue for non-renewable. [9]

The land scarcity, especially in Europe, has lead to development of offshore wind farms that are now operating successfully. Furthermore, the interest floating solar in the form of floating photo voltaic (FPV) has increased. Several FPV installations on inland water bodies are in operation already [10]. In addition to the advantage of avoiding land occupation, FPV installations have the benefit of the cooling effect of the water. Therefore, a higher efficiency is achieved with FPV than with land-based photo voltaic systems [11]. So for both wind and solar energy harnessing, locating the farms offshore has benefits. And by combining the solar and wind energy generation offshore an increased power output per unit surface area and a reduction in the temporal variability of the output would be realised compared to non-hybrid energy harnessing farms. In addition, the electricity infrastructure can be combined for the wind and solar facilities, thereby reduce construction costs.[1]

1.1. Problem description

The potential of FPV and the benefit of combining wind and solar have lead to the interest in an offshore wind and solar farm (OWSF) . Research is being conducted on the electrical integration of the wind and solar installations [12] and the optimal design of offshore FPV [13][14]. One of the remaining uncertainties around the feasibility of an OWSF is the operations and maintenance (O&M) cost [2]. O&M of offshore wind farms is well developed, but is still facing important challenges. O&M costs accounts for 25% of the life cycle costs of offshore wind farms. Revenue losses and downtime account for 25% of the O&M costs [15]. An important contributor to the revenue losses and downtime is accessibility. Small weather windows due to the combination of bad weather conditions and regulations, especially safety regulations, decrease accessibility and therefore decrease the availability of the wind farm [3]. O&M support strategies are being investigated for offshore wind farms that make better use of the weather windows and vessel transfers possible. O&M support consists of the logistic operations that make sure that the personnel, equipment and spare parts are at the right place at the right time. Nguyen et al. [4] and Zhou et al. [5] showed that an improved O&M support strategy can reduce the O&M cost with 4.56% and 39.24% respectively. As offshore floating solar will likewise face challenges in accessibility due to the combination of bad weather conditions and safety regulations, it will as well require an optimal O&M support strategy.

The largest part of O&M support for offshore wind farms is the logistic operation for the maintenance tasks [4]. Therefore, this research focuses on the logistic aspect of the maintenance operation i.e. the offshore maintenance support. In logistic operations for the maintenance of offshore wind farms decisions are made at different levels. Shafiee [16] divided it in strategic, tactical and operational decisions (see figure 1.2). Strategic decisions are long-term decisions and include maintenance strategy selection, location and capacity of maintenance bases, and outsourcing decisions. Tactical decisions include spare part supply and storage, and vessel purchasing or leasing decisions. At the operational level decisions are made for scheduling of the maintenance and routing of the vessels. In the maintenance logistics of an OWSF, decisions at each level influence the decisions at the other levels. For instance the strategic choice of where to locate the maintenance base influences the tactical choice of which type of vessel to use and this decision affects the maintenance schedule and vessel route plan. In an OWSF the most immediate question is: Should the maintenance support of the wind turbines and floating solar units be integrated? Because the maintenance support of operational offshore wind farms is already existing, the organization could include the maintenance of the floating solar units. In order to find the answer for this question research is needed to analyse the advantages and disadvantages of combining the maintenance support of wind and solar at operational level, i.e. in the routing and scheduling of the vessels.

Multiple studies are conducted to tackle the maintenance schedule and vessel routing problem of wind farms. The studies can be broadly categorized in simulation-based ([17], [18], [19], [20], [21], [22], [23], [24], [25], [26], [27]) and optimization based ([28],[29], [30], [31], [32], [6], [33], [34], [35], [36], [37]). The simulation models simulate the maintenance operations for the entire life cycle of the wind farm. Optimization models use regularly updated forecasts to optimize the maintenance schedule and routing within the planning horizon. As an OWSF is a new concept, studies have not been conducted to investigate the scheduling and routing of maintenance support vessels including FPV maintenance.

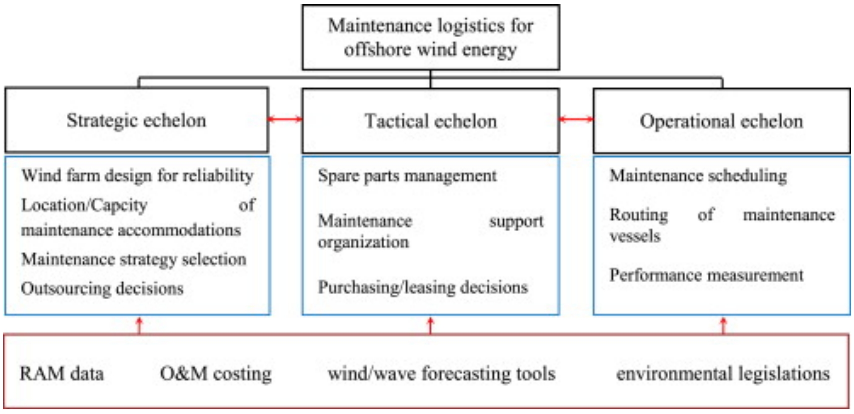


Figure 1.2: Decision making in maintenance logistics of offshore wind farms [16]

1.2. The aim of this research

This research aims to develop an optimal route and schedule of the maintenance support vessels for an OWSF. The maintenance of the wind and solar installations can be addressed separately as the units differ in many respects. However, it is expected that combining the offshore logistics of the wind turbine and solar unit maintenance tasks will be advantageous because of the high cost of the operation and small time windows due to weather conditions. Combining the maintenance support has the potential to increase the effective use of the time windows and the vessel transfers. For this reason, the maintenance support of an OWSF is addressed as one operation with focus on the routing and scheduling of the vessels.

This project proposes an optimization model in order to develop an optimal route and schedule of maintenance support vessels for offshore wind and solar farms. It main contributions are:

- A summary of the state of the art of maintenance support vessel routing and scheduling for offshore wind farms.
- An optimization model for routes and schedules of maintenance support vessels for an offshore wind and solar farm.
- Recommendations for further development of maintenance support strategies for offshore wind and solar farms.

1.3. Research questions

In this research the main research question is:
What is the optimal route and schedule of maintenance support vessels for an offshore integrated wind and solar farm?

The research question will be answered according to the following sub-questions:

1. *What is required to develop an optimal route and schedule of maintenance support vessels for offshore wind and solar farms?*
   The concept of offshore solar farms and the concept of a combined wind and solar farm offshore are rather new. Therefore, literature study is performed to investigate what the requirements are for an optimal route and schedule of maintenance support vessels for an OWSF and which method can be used to develop this optimal route and schedule.
2. *What methods are developed for the optimization of the route and schedule of maintenance support vessels for an offshore wind farm and which method is most applicable for an offshore wind and solar farm?*
   A substantial amount of research is performed to develop optimization models for the route and schedule of maintenance support vessels for offshore wind farms. Literature study is performed

to understand and summarize the methods used in these studies. On the basis of the literature study and the model requirements the most applicable method is chosen.

3. *Is the chosen optimization method fully applicable for route and schedule optimization of maintenance support vessel of an OWSF, if not which adjustments are required?*
From the summarized methods for optimizing maintenance support vessel route and schedules of offshore wind farms, the method that is most applicable for optimizing maintenance support vessel route and schedules of offshore wind and solar farms.

4. *Is the optimization model for maintenance support vessel routing and scheduling for an OWSF correctly implemented?*
In order to apply the optimization model to find the optimal route and schedule of maintenance support vessels for a case study OWSF, the model is implemented in Python. By answering this sub-question the model implementation can be verified.

5. *What is the optimal route and schedule of maintenance support vessels for an offshore wind and solar farm case study?*
To answer the main research question a case study is performed. The results of the case study give insight in whether the optimal route and schedule of maintenance support vessel for an OWSF include combined transport for wind turbine maintenance and solar unit maintenance.

6. *How can the optimal route and schedule for maintenance support vessels for the case study be validated?*
The main question in the maintenance support of an OWSF is whether combining the maintenance support for the wind turbines and floating solar units is cost beneficial. Therefore, multiple analysis are performed to investigate the dependency of the optimality of combining the transport on different input parameters.

1.4. Scope of the research

This research gives insight in the offshore maintenance support operation of an OWSF. It provides recommendations for the development of an optimal offshore maintenance support strategy of an OWSF. The development of an OWSF is in a very early stage. No comparable offshore floating solar installations are in operation. Research is only performed to investigate the feasibility of offshore floating solar farms in itself and the feasibility of an OWSF in terms of electrical integration. Therefore, numerous assumptions are made in the maintenance tasks and maintenance support of the floating solar units. Furthermore, as the maintenance support of an OWSF will be a complex and extended operation multiple demarcations have been applied. The main demarcations are: the use of only three types of maintenance support vessels, excluding the maintenance of submarine electricity cables, and not considering different type of technicians for different maintenance tasks. The assumptions and demarcations related to the OWSF maintenance support are further elaborated in chapter 2.
The model used to find the optimal route and schedule of the maintenance support vessels is developed for research purposes only. The required computational time and capacity limitations make the model not suitable for operational purposes. The applicability for different OWSFs is taken into account in the development of the model. The choices made in developing the model are further discussed in chapter 3.

1.5. Structure of the report

The following chapters answer each a sub-question of the research. Chapter 2 answers sub-question 1 by explaining what is required for an optimal route and schedule of maintenance support vessels for an OWSF. Chapter 3 answers sub-question 2 by means of describing the methods for maintenance support vessel route and schedule optimization for offshore wind farms. It provides an explanation of the selection of the method that forms a base for the OWSF maintenance support vessel route and schedule optimization model. Chapter 4 explains the chosen method in detail and describes the required adjustments to make it applicable for an OWSF. Hereby the chapter answers sub-question 3. Sub-question 4 is answered in chapter 5. It verifies the developed model for maintenance support vessel route and schedule optimization for OWSFs. Chapter 6 describes the case study and its results and validates the results. Chapter 7 concludes and discusses the research and provides recommendations for further research.

2

Maintenance support requirements for an OWSF

This chapter gives answer to the sub-question *What is required to develop an optimal route and schedule of maintenance support vessels for offshore wind and solar farms?*. In order to develop the optimal maintenance support vessel route and schedule for an offshore wind and solar farm, understanding of the concept and maintenance support in general is required. Section 2.1 describes the concept of a combined offshore wind and solar farm. Section 2.2 gives a description of the expected requirements for the operation and maintenance of offshore wind and solar farms. Section 2.3 concludes the chapter by listing the main requirements for an maintenance support vessel route and schedule optimization model for an OWSF.

2.1. Concept description

The offshore wind and solar farm addressed in this research consists of non-floating wind turbines and floating photovoltaic panels (FPV) (see figure 2.1 and 2.2 resp.). The wind turbines are positioned in a general offshore wind farm set-up and the FPV units are positioned near or between the turbines.

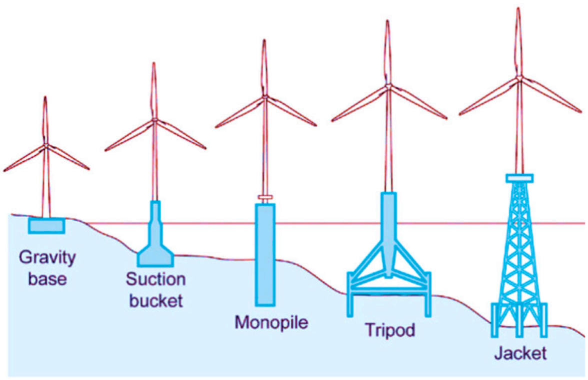


Figure 2.1: Typical fixed base foundations of offshore wind turbines [38]

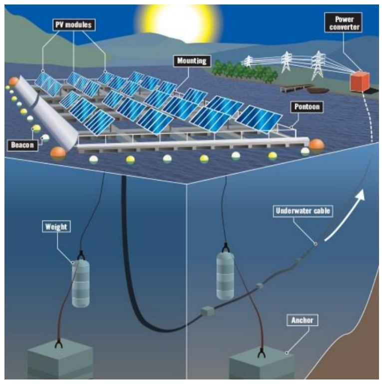


Figure 2.2: An example of FPV with an anchoring system [39]

As offshore FPV is a rather new concept very little is known about its design. The development of offshore FPV is done by startups that are typically not interested to publish technology data or first experiences because this may adversely effect interests of investors and increase competition. Therefore, not many open reports or technical data and drawings are available. However, to get an impression of what the design of the floating solar units could look like figure 2.3a, 2.3b, 2.3c, and 2.3d show designs installed at near shore locations.

(a) Pilot of Oceans of Energy [40]

(b) FPV design of Swimsol [41]

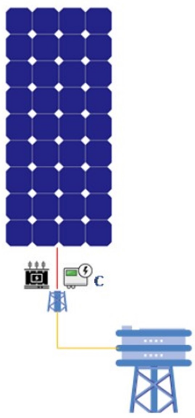
(c) FPV design of Oceansun [42]

(d) FPV power plant of Sunseap Group [43]

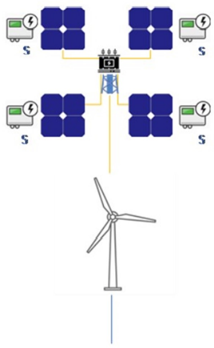
Figure 2.3: Several near shore floating solar installations

A TNO research conducted by Houwing et al. [12] investigating the feasibility of an OWSF suggests three feasible concepts. The main distinction between the concepts is the electrical integration of the FPV installations with the wind farm. Three methods of electrical integration can be distinguished:

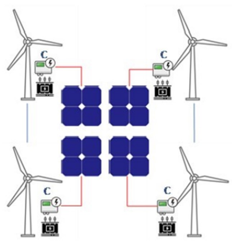
- Standalone: The FPV power plant is located close to the wind farm and connected to the same substation for electricity transfer to the shore (see figure 2.4a).
- Semi-standalone: A block of multiple PV floaters is connected to the same string as the wind turbine. In this way multiple blocks are connected to different strings (see figure 2.4b). The PV floaters are connected to the electricity infrastructure of the wind farm. The distance between the PV blocks and the nearest wind turbine will be around 2km.
- Integrated: The small FPV blocks are connected to the wind turbines using the inverter and transformer located at the turbine (see figure 2.4c). The distance between the PV block and the wind turbine will be around 500m.



(a) Standalone concept



(b) Semi-standalone concept



(c) Integrated concept

Figure 2.4: Feasible electrical integration concepts according to Houwing et al. [12]

In this research the OWSF is considered to be constructed in an integrated manner. This means that the FPV units are located in between the wind turbines taken into account that the FPV units and turbines are accessed separately. Vessels can navigate between the turbines and solar units. Figure 2.5 gives a representation of the concept.

Figure 2.5: An OWSF concept representation [44]

2.2. Description of OWSF maintenance support

Operations and maintenance activities have the purpose to keep the system running as a whole. Where operations refers to the high level management of the asset and maintenance refers to the up-keep and repair of the physical systems [45]. In order to maintain offshore installations, logistic operations are required to transport the technicians and spare parts to the right location at the right time. The logistic operation for offshore maintenance is referred to as maintenance support. Because an OWSF is a new concept as well as offshore floating solar farms, the maintenance support of offshore wind farms forms the base in this research for the development of the maintenance support of an OWSF. Figure 2.6 illustrates an overview of the main aspects of the O&M of offshore wind farms.

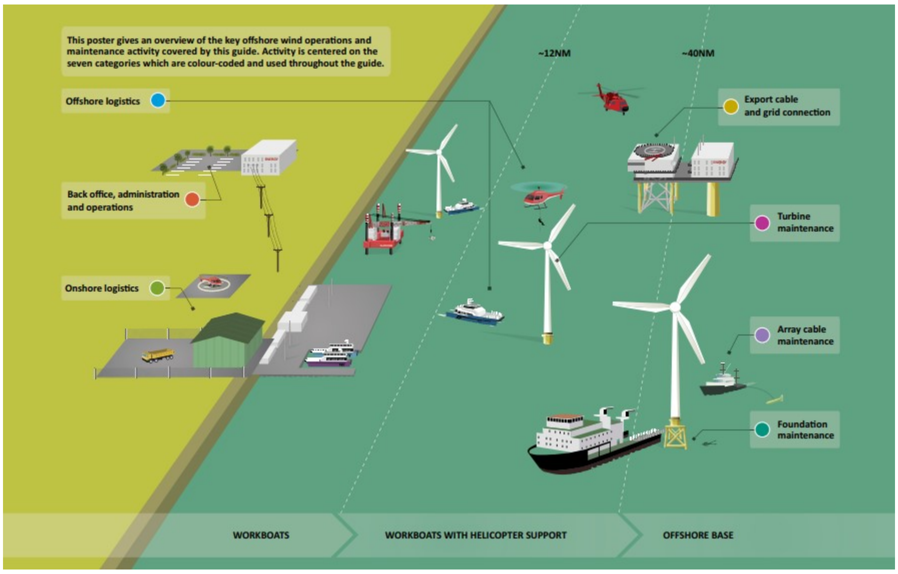


Figure 2.6: Illustration of main aspects of offshore wind O&M [45]

The maintenance support of offshore wind farms can be divided in offshore and onshore logistics [45]. Onshore logistics consist of port facilities and spare part supply and storage. The offshore logistics consist of transferring crew, equipment and spare parts to the turbines or other farm infrastructure, such as offshore substations. This research focuses on the offshore maintenance support. The main factors that determine the maintenance support strategy are the distance from shore; average sea state; number, size and reliability of the turbines; and offshore substation design. Dewan and Aspargarpour [15] describe different maintenance support strategies, of which following strategies are deployed :

- Shore based maintenance support strategy
  The maintenance base is located at the shore. Crew Transfer Vessels (CTV) (see figure 2.8) and in some cases helicopters are used to transfer technicians and spare parts from shore to the wind turbines and substations. When heavier spare parts need to be transported bigger vessels are needed such as a jack-up barge vessel. Shore based strategies are only feasible for near shore wind farms. This is the most basic strategy and is for instance implemented in OWEZ (Offshore Windpark Egmond aan Zee) in the Netherlands.

- Offshore based maintenance support strategy
  The maintenance base is located offshore, close to the wind farm. This maintenance base can be a permanent base installed at sea or a Service Operating Vessel (SOV) (see figure 2.9) as floating base. Technicians and smaller spare parts are located at the offshore base. The SOV itself can provide the transfer of personnel and equipment to the turbines. In case of a permanent base, vessels or helicopters are required to provide the transfer to the turbines. Offshore based O&M is more applicable for far-offshore wind farms (>50km) as it is an expensive strategy and the transit time only decreases significantly when the wind farms are located far from shore. Horns Rev 2 in Denmark and DanTysk in Germany chose for this strategy.

In addition to the choice for shore or offshore based maintenance support, a maintenance support strategy includes other decisions. As described by Shaffiee [16] it also includes maintenance strategy selection, and outsourcing decisions.

Maintenance actions are performed according to a chosen maintenance strategy. Figure 2.7 shows the most commonly deployed maintenance strategies in offshore wind farm maintenance. Preventive maintenance strategy implies maintenance activities that are performed to prevent component breakdown. Preventive maintenance is calendar based when it is scheduled according to fixed time intervals or a fixed number of operating hours. When the maintenance is based on actual health of the system it is called condition based maintenance. Corrective maintenance is a strategy where maintenance is performed after a failure or breakdown has occurred. Depending on the failure a maintenance activity can be executed immediately or later in time. Immediate maintenance actions are taken with an unplanned corrective maintenance strategy. For a planned corrective maintenance strategy action is planned when degradation is observed.

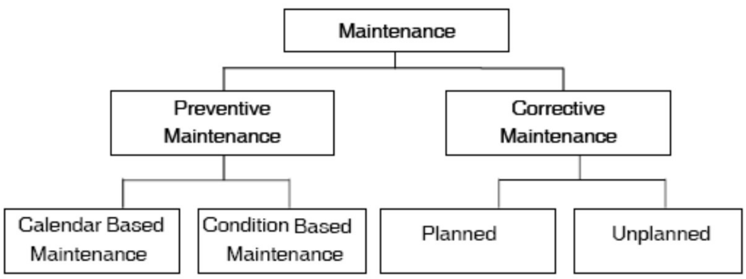


Figure 2.7: Maintenance strategies [46]

An other form of preventive maintenance that is considered to be a cost efficient strategy for offshore wind farms is opportunistic preventive maintenance, because of the high expenses of the offshore maintenance logistics and the small weather windows. Opportunistic preventive maintenance means taking preventive maintenance action whenever the opportunity arises to minimize failure. [27]

When strategic decisions are made for the maintenance support, tactical decisions can be made. Tactical decisions in the maintenance support of offshore wind farms include spare part management, the maintenance support organization and purchasing or leasing decisions. When going further into detail operational decisions are made. The scheduling and routing of the maintenance support vessels is part of the operational decisions. With the vessel and technician availability and the maintenance strategy the maintenance tasks are scheduled and the daily vessel routing is determined.

For wind farms the maintenance tasks can be divided in turbine maintenance, foundation maintenance and array cable maintenance [45]. With array cable is meant the electricity cables between the wind turbines. The maintenance support vessels that are used for offshore wind farms are the earlier described SOV and CTV, a diving support vessel, and cable laying vessels [47]. Furthermore, helicopters can be used for the transfer of small spare parts and technicians [45].

In an OWSF the components that enable the solar energy harnessing have in many aspects the same demands for the offshore maintenance support. Multiple types of technicians, spare parts and tools are required at site in order to perform the maintenance tasks. Maintenance tasks for floating solar generally includes PV panel and cabling maintenance, mooring system maintenance, and submarine cable maintenance [2]. Vessels are needed to transport the technicians, spare parts and tools from the port to the floating solar units. Furthermore, FPV generally has a lot of components below water level and specialized divers are necessary to inspect the components and perform small repairs. FPV is commonly accessed by an RHIB, which are small boats that have a relative small personnel and weight capacity (see figure 2.10).

Figure 2.8: An example of an CTV [48]

Figure 2.9: An example of an SOV [49]

Figure 2.10: An example of an RHIB [50]

2.3. Model requirements

A number of studies is performed to develop routing and scheduling models for offshore wind farms. As stated in chapter 1 the studies can be broadly categorized in simulation-based ([17], [18], [19], [20], [21], [23], [24], [25], [22], [26], [27]) and optimization based ([28],[29], [30], [31], [32], [6], [33], [34], [35], [36], [37]). The simulation based studies require a lot of data in order to simulate the maintenance operation. Because an OWSF is a new concept not much data is available. Furthermore, when a simulation model is used to find the optimal routing and scheduling, a large number of possible simulation scenarios must be generated because of the dynamic level and uncertain behaviour of the maintenance support operation. With a large number of units that need maintenance, a large number of shifts when maintenance can be performed, and multiple vessels that can provide the resources for the maintenance a lot of different scenarios are feasible. It is impossible to run and compare all these scenarios to choose the optimal one [51]. By modelling the routing and scheduling as an optimization problem the decisions made by the model can be analyzed. For instance, if the solution contains separate routes for solar and wind the conclusion might be that the combination of the maintenance support of wind and solar is not favourable. Therefore, the research is focused on an optimization model for routing and scheduling of an OWSF.

This chapter described the expected general characteristics of maintenance support of an OWSF. In the development of the model as much as possible characteristics must be included in order to meet the state of the art in route and schedule optimization models for offshore maintenance support vessels. However, a few assumptions and demarcations are applied. Firstly, it is assumed that the maintenance tasks that should be performed in the planning period are known beforehand. The model gets inputted a number of tasks that should be performed in the analysed period (planning period) and schedules the tasks in that planning period. The tasks that should be performed are determined according to a maintenance strategy. The model takes into account the differences in characteristics of preventive and corrective maintenance tasks, but all required tasks for the planning period must be known before running the model. Secondly, in this research it is assumed that an FPV unit can be accessed with a CTV and an SOV additionally to an RHIB. Currently, FPV is accessed by RHIBs. Whether CTVs and SOVs can access the FPV is still unclear, but in order to show the potential of combining the vessel transits to the FPV and turbines it is assumed that the FPV can be accessed by a CTV and an SOV. Furthermore. Only access vessels are considered in the route and schedule optimization, i.e. SOV, CTV, and RHIB. Related to that, only maintenance that can be performed with these access vessels is taken into account. The maintenance of array cables and foundation maintenance that requires divers is performed with support of vessels that are not used for accessing the turbines or FPV units [47]. Therefore, it can be considered as a separate operation. The use of an helicopter is not accounted for because it is generally used for unplanned, immediate maintenance [3] and the model considered maintenance tasks as planned maintenance for the analysed period.

On the basis of the explained information in this chapter about the routing and scheduling of maintenance support vessels, the requirements for the optimization model are listed below. An optimization model for the routing and schedule of maintenance support vessels of an OWSF should include the following aspects:

- Maintenance tasks are allocated to different nodes
  In order to allocate solar unit maintenance tasks to solar unit nodes and wind turbine maintenance tasks to wind turbine nodes, the model must include the ability to allocate different maintenance tasks to different nodes.

- Multiple vessels with different routes
  The model must be able to construct the route and schedule for multiple vessels during the same shift. This gives the model the ability to choose for one vessel to transfer technicians and spare parts to the turbines and FPV units or to choose for assigning separate vessels for the wind and solar unit maintenance.

- Different characteristics for vessels
  This research takes three types of maintenance support vessels into account. The differences between the vessel types must be considered in the model.

- Multiple service orders per tour
  The aim of the model is to find the optimal route and schedule for maintenance support vessels of an OWSF. An important aspect of this route is the combination of the transport for solar and wind service orders. In order to enable the model to choose for combined transport, the vessel must be able to perform multiple service orders during one tour.

- Downtime cost related to the maintenance task
  As the wind turbines and the solar units have different power curves. The downtime cost per unit (solar or wind) is different. These discrepancies in downtime cost per maintenance tasks must be accounted for in the optimization model.

- Downtime cost related to weather conditions
  In addition to assigning the different downtime cost to different maintenance tasks, different downtime cost must be assigned to different shifts. During a shift the weather conditions can result in higher downtime cost due to the failure of solar components then due to the failure of wind components or the other way around.

- Distinction between preventive and corrective maintenance tasks
  Related to the downtime cost, the differences in preventive and corrective maintenance tasks must be acknowledged in the optimization model. Corrective maintenance tasks are scheduled after a failure, this means that the downtime starts when the failure occurs and ends after the task

is performed. In the contrary the downtime of preventive maintenance is only equal to the time the task is being performed.

3

Maintenance support vessel route and schedule optimization methods for offshore wind farms

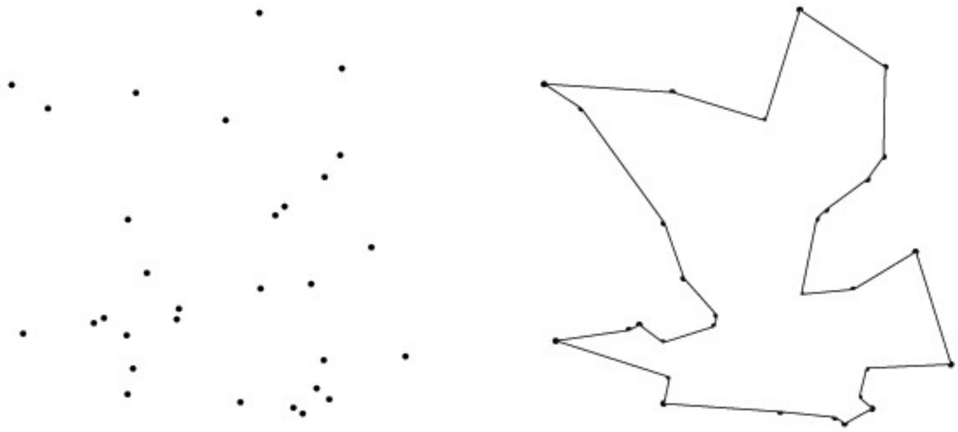
This chapter answers the sub-question *What methods are developed for the optimization of the route and schedule of maintenance support vessels for an offshore wind farm and which method is most applicable for an offshore wind and solar farm?*. As explained in the previous chapter, this research requires an route and schedule optimization model. Route and schedule optimization models in general exist of a mathematical model and a solution method. Section 3.1 describes what is meant by a mathematical model for routing and scheduling problems and section 3.2 explains how the mathematical models of maintenance support vessels are formulated in offshore wind farm research. Section 3.3 describes what solution methods are developed to solve routing and scheduling problems of maintenance support vessels for offshore wind farms and section 3.4 explains the solution methods used or developed for the routing and scheduling optimization of offshore wind farms. Section 3.5 describes the process of choosing the most applicable mathematical model and solution method for this research.

3.1. General description of routing and scheduling problems

As the previous chapter explains, the scheduling and routing of offshore farms is a complex and challenging problem. Weather conditions, the availability of resources (e.g. service vessels, crew, and spare parts), safety regulations and the losses in electricity generation should be considered. Generally in a scheduling and routing problem, the route specifies the sequence of locations to be visited and the schedule identifies the times at which the activities at these locations are to be carried out. Routing and scheduling problems are characterised by task precedence and time window constraints. For instance, one vehicle should first visit location 'A' for pick up and later location 'B' for delivery. Where location 'B' can only be visited during a certain time window. [52] To understand what the possibilities are to approach the routing and scheduling problem, first routing problems are explained.

3.1.1. Routing problem

The Vehicle Routing Problem (VRP) is a problem formulation first introduced by Dantzig and Ramser in 1959 [53]. The goal of the VRP is to determine for a fleet of vehicles an optimal set of routes to serve a set of customers. It is now the most widely researched combinatorial optimisation method. The VRP is a generalisation of the earlier introduced Traveling Salesman Problem (TSP) by W.R. Hamelton in the 1800s but first published by M. M. Flood in 1956 [54]. The TSP is a problem formulation with the aim to find the optimal route along a given set of locations while minimizing distance, cost, or time (see figure 3.1). In a TSP there is only one vehicle that can visit each location only once and the starting point is the same location as the ending point. When formulating the VRP different characteristics for the problem can be chosen.



(a) Problem input [55]

(b) Problem solution [55]

Figure 3.1: An example for the Traveling Salesman Problem

The classical VRP is defined on an undirected graph $G = (N, A)$ where $N = 0, 1, ..., n$ is the set of nodes and $A = (i, j) : i, j \in V, i \neq j$ is the set of arcs [56]. The node 0 mostly represents the depot at which K vehicles $V = 1, 2, ..., v$ with capacity b_v are located. Each customer $i \in V/0$ is associated with a non-negative demand q_j of customer j which is in the classical VRP smaller than the vehicle capacity b_v. Furthermore, the cost of including an arc in the route is specified in the cost matrix c_{ij}. The mathematical model of a vehicle routing problem starts with the objective function. The objective function represents the measure for when a solution is optimal. A classic example of the objective function is:

$$Min \sum_{i=0}^{N} \sum_{j=0}^{N} \sum_{v=1}^{V} c_{ij} y_{ijv} \tag{3.1}$$

In this formulation y_{ijv} is a binary variable that has the value 1 if the arc from i to j is part of the route of vehicle v, otherwise it is 0. y_{ijv} is a decision variable, the value of this variable will be decided when solving the VRP. An other decision variable typical for the VRP is the binary variable, here called z_{iv}, that indicates whether customer i is visited by vehicle v. It is 1 if the visit of customer i by vehicle v is included in the solution. According to this objective function the cost must be minimized. When the objective is determined, constraints are formulated to ensure that the solution is feasible and meets the restrictions of the problem. Constraints associated with the above described classical VRP are:

$$\sum_{v=1}^{V} z_{iv} = 1, \qquad \forall i (i \neq 0) \tag{3.2}$$

$$\sum_{v=1}^{V} z_{0v} = K, \tag{3.3}$$

$$\sum_{i=1}^{N} q_i z_{iv} \leq b_v, \qquad \forall v \tag{3.4}$$

$$\sum_{j=0}^{N} y_{ijv} = \sum_{j=0}^{N} y_{jiv} = z_{iv}, \qquad \forall v, i \tag{3.5}$$

$$\sum_{i \in S}^{N} \sum_{j \in S}^{N} y_{ijv} \leq |S| - 1, \qquad \forall v, S \subset V \tag{3.6}$$

Constraints 3.2 makes sure that each node is visited by one vehicle. Constraint 3.3 ensures all vehicles leave the depot. With K as the total number of vehicles. Constraint 3.4 states that the demand q of the customer i visited by vehicle v should be less or equal to the capacity b_v of the vehicle. Constraint 3.5 determines that if customer i is visited, the arc to the node and the arc from the node are included in the solution route. Constraint 3.6 eliminates sub-tours, where S is a number of nodes in the set of customers N. This manner of sub-tour elimination is proposed by Dantzig, Fulkerson, and Johnson [57].

The VRP has many variants. It can differ in objective function and constraints depending on the practical problem that is considered. Several variants are described in section 3.2 when the approach of earlier studies about the routing and scheduling of maintenance support vessels of offshore wind farms is discussed.

3.1.2. Scheduling problem

Routing problems have multiple similarities with scheduling problems. Vehicle and crew scheduling problems can be considered as VRP with additional constraints related to the time at which the activities may be executed [52].

To understand the nature of the temporal constraints the following example is given: A package should be delivered at the location 'A' and it is known that once the vehicle is arrived the delivery will take exactly 10 minutes. This constraint can be implemented as a weight (10 minutes) associated with the delivery task with an other constraint to limit the route time to a certain number (like a working day of 8 hours). When applying a routing mathematical formulation to solve this problem, it can assign the delivery to location 'A' to any time of the day. If the time is specified when the delivery to 'A' should take place, the delivery is associated with a start time and an end time. For instance, a start time of 10.00 AM and an end time of 10.10 AM. For this problem a scheduling mathematical formulation is more applicable. [52]

An example of a temporal time constraint that can be added to the routing problem formulation in section 3.1.1 is formulated in equation 3.7. Where t_{iv} is the time the vehicle visits customer i as a decision variable. y_{ijv} is the binary decision variable that states whether vehicle v travels directly from i to j. z_{iv} is a binary decision variable that indicates whether customer i is visited by vehicle v. L_i is the determined lower limit for the time to visit node i. This constraint ensures that the time customer i is visited is greater than or equal to the specified lower limit of the visit to node i.

$$t_{iv} \geq L_i z_{iv}, \qquad \forall i, v \tag{3.7}$$

For the routing and scheduling of maintenance support vessels for an offshore wind and solar farm a combination of routing and scheduling problem applies. The optimal schedule of the maintenance tasks influences the routing of the vessels, and the optimal routing influences the schedule of the maintenance activities.

3.2. Routing and scheduling for offshore wind farms

Research conducted to formulate the routing and scheduling problem of maintenance support vessels of offshore wind farms is helpful in developing the applicable mathematical formulation for the routing and scheduling of maintenance support vessels for an OWSF. This section describes the maintenance support vessel routing and scheduling problem formulations in offshore wind farms maintenance research.

To the authors knowledge, the first optimization model developed to optimize the maintenance planning of offshore wind farms is proposed by Besnard et al. in 2009 [58]. The model is a linear integer optimization model with an objective function that minimizes the production losses and the transportation costs. It includes a short and long horizon interval to schedule the maintenance tasks. The model uses the opportunity of required corrective maintenance tasks of one turbine to perform the upcoming planned preventive maintenance tasks of that turbine at the same time. In 2011 Besnard et al.

[59] improved the model with a rolling horizon principle with including updated weather and production forecast for the planning horizon. Therefore, the model became a stochastic optimization model for opportunistic service maintenance of offshore wind farms. Moreover, constraints on accessibility to the wind turbines are added. However, it does not include the routing of the vessels. In 2013 Besnard et al. [60] proposed a new model that computes the performance of a maintenance support of offshore wind farms with alternative transportation means. Only the decision of on which day to perform the maintenance tasks is taken in the model, but the routing of the vessel is not considered.

Halvorsen-Weare et al. [61] proposed a deterministic vessel fleet optimization model for maintenance at offshore wind farms. It is developed to evaluate which vessel types should be purchased, which should be chartered-in, and which infrastructure (such as vessel bases both offshore and on-shore) should be used. The model incorporates preventive and corrective maintenance tasks but treats both types of tasks as known, i.e. at the start of the planning horizon the failures are known. Preventive maintenance tasks have a soft time window and a hard time window with a penalty cost. A soft time window represents the preferred time window for when to perform the task. It is implemented with assigning a penalty cost for not performing the task. The hard time window is implemented as a constraint. Several types of vessels can be purchased or leased. Each vessel type has a given spare part and personnel capacity, a given service speed, and operational weather requirements. The vessels weather requirements and the weather forecast limit the time intervals for which the vessel can operate.The objective function of the mathematical model minimizes the cost of vessel fleet and infrastructure, expected downtime costs, penalty costs, and transportation costs. The fleet optimization problem is a strategic decision, which should be made in the design phase of a project. It does not provide operational scheduling and routing for offshore wind farms.

The proposed model of Dai et al. [29] is the first model to the authors knowledge that investigates the operational decision problem of routing and scheduling of a maintenance fleet for offshore wind farms. The problem is modeled as a Vehicle Routing Problem with Pick-up and Delivery (VRPDP) , but with a few adjustments compared to the traditional version. The problem is a multi-period problem and the length of the time periods varies for each vehicle. There is a penalty cost, which differs per node, for delaying the visit of the node to a different time period. Furthermore, it includes two types of capacity constraints on the vehicles, limiting the number of personnel and limiting the weight of the equipment transported. Finally, includes this model the requirement for some pick-up/delivery pairs that the vehicle travels directly from the delivery node to the pickup node.

In the literature a division in research focus is noticed. Studies are conducted to optimize the vessel fleet composition of offshore wind farm maintenance operations ([62],[19],[20],[63], and [31]) like the study of Halvorsen-Weare et al.[61]. Other studies are focused on optimization of the operational decision problem of routing and scheduling of the maintenance of offshore wind farms, like the studie of Dai et al. [29]. As this research aims to develop a routing and scheduling optimization model for offshore wind and solar farms, the studies investigating the routing and scheduling problem are described.

Stålhane et al. [34] modeled the scheduling and routing problem of offshore wind farms as a similar problem. The main differences are the more detailed calculation of the downtime costs and the introduction of an efficient solution method for this problem. In order to implement the proposed solution method the problem is formulated as an arc-flow and reformulated as a path-flow model by using the Dantzig-Wolfe decomposition [64]. The problem is divided into sub-problems. Where first all feasible routes are determined. The feasible routes are inputted in the path-flow model and the optimal combination of routes is outputted. The description of the solution method used by Stålhane et al. is included in section 3.4.

Dawid et al. [65] developed an O&M tool that recommends an on-the-day vessel routing. It minimizes cost and maximizes the number of repaired turbines. The routing problem is modeled as a VRPDP adjusted constraints related to the required transfer time, the variable vessel speed (at open sea or traversing a wind farm), and the reuse of resources (one crew performing maintenance at multiple turbines). The model only analyzes the routing problem for a given schedule.

Another research is performed that does not consider routing. Tan et al. [66] developed a model that represents the scheduling problem of offshore wind farm maintenance. The problem is modeled as a multi-integer linear programming problem. It includes resource and supply costs, transportation costs, labor cost, and production loss due to maintenance. The solution contains which task at which time and by which team.

Another study investigating the routing and scheduling problem of offshore wind farms is performed by Irawan et al. [32]. The difference with the studies of Dai et al. [29] and Stålhane et al. [34] is the consideration of multiple O&M bases and multiple wind farms. Irawan et al. also relate their mathematical model to the VRPDP.

Raknes et al. [6] modeled the routing and scheduling problem for offshore wind farms with several similarities with the work-over rig routing problem (WRRP) . The WRRP has its origins in onshore oilfield O&M, where a set of work-over facilities at different locations carry out maintenance on oil wells. For safety reasons, production from a well in need of maintenance is reduced or stopped. The aim of the WRRP is to minimize total lost production. Compared to the studies described above the study of Raknes et al. provides an extension by considering a combination of vessels that can stay offshore for several periods and vessels that must return to the depot between each shift.

Schrotenboer et al. [33] developed a model that generalizes the earlier proposed models for the routing and scheduling optimization of offshore wind farms [29][32][34]. The problem is formulated as a Technician Allocation and Routing Problem (TARP) . The goal of the proposed model is to determine the daily allocation of differently skilled technicians to multiple O&M bases and the associated daily vessel routes for execution of the maintenance tasks. In the TARP, technicians are flexibly allocated on a daily basis. Two variants of the TARP are introduced: TARP-F and TARP-G. The TARP-F variant allocates technicians at the beginning of the time horizon and this allocation remains fixed over the time horizon. The TARP-G variant uses a given allocation of the technicians, this model represents the case where technicians are not shared between O&M bases. According to the study of Schrotenboer et al. the TARP can be classified as a new variant of the multi-depot multi-period pickup and delivery problem with multiple commodities or a combination of a one-to-one and many-to-many pickup and delivery structure.

A novel operational planning methodology based on two types of vessels that can be used separately or combined is proposed by Lazakis et al. [36]. It represents a realistic scenario on the usage of SOV's, CTV's or a combination of the two for the daily route planning. It considers vessels specifications, climate data, failure information, wind farm attributes and cost-related specifics. The optimization problem is simplified by dividing the series of operational tasks into sequential sessions: technician drop-off and pick-up sessions. The drop-off session consists of the SOV leaving the port or its standby location, visiting the turbines to drop-off the technicians, and when required the stay of the SOV at the turbine. The required staying of the SOV at a turbine is categorized as near-stay or far-stay. The SOV stays, according to the industry standard, at a distance equal to one unit of the overall length of the vessel from the turbine for a near-stay. For a far-stay, the SOV waits at a determined location relatively close to the turbine. The pick-up session begins when the technicians are dropped-off at the last turbine or the near- or far-stay for the last turbine is completed. The pick-up session consists of the route planning to pick up the technicians from the turbines. The vessel routing optimization is performed separately for both sessions. The sum of fuel consumption, cost and overall time required to complete all maintenance tasks is minimized over both sessions.

Allal et al. [51] proposed an combined optimization and simulation method for optimizing route and schedule of offshore wind farms. During the simulation process, the optimization algorithm provides a more realistic decision to reduce the number of possible simulation scenarios. The optimization problem is formulated as a VRPDP with the objective to minimize the transport costs. The model considers a heterogeneous fleet of vessels with limited tour duration according to the maintenance team working time. It includes turbine visit urgency based on the required corrective maintenance or the preventive maintenance thresholds.

Figure 3.2 gives a summary of the studies that provided a mathematical formulation of the maintenance support vessel routing and scheduling problem for offshore wind farms. It summarizes the characteristics of the routing and scheduling problem that are included in the model.

	Dai et al. (2015) [28]	Stålhane et al. (2015) [34]	Dawid et al. (2016) [63]	Tan et al. (2017) [64]	Irawan et al. (2017) [31]	Raknes et al. (2017) [32]	Schrotenboer et al. (2018) [33]	Lazakis et al. (2021) [36]	Allal et al. (2021) [49]
Nodes									
One depot	v	v	v	v		v		v	v
Turbines represented as nodes	v	v	v					v	v
Resources									
Multiple vessels	v	v	v	v	v	v	v	v	v
Multiple vessel types						v	v	v	
Vessel capacity for equipment weight	v	v	v			v	v	v	
Vessel capacity for technicians	v	v	v	v	v	v	v	v	v
Multiple technician types					v		v		v
Maintenance tasks									
Multiple maintenance tasks per turbine		v	v		v	v			
Multiple maintenance tasks per vessel route			v	v				v	v
Variable number of technicians per maintenance task		v		v				v	
Variable vessel requirements per maintenance task						v		v	
Preventive maintenance tasks		v		v	v	v	v	v	v
Corrective maintenance tasks		v				v	v	v	v
Task urgency			v		v	v			v
The vessel stay requirement for a task	v				v	v	v	v	
Time constraints									
Multiple periods	v				v		v		v
Varying offshore time length per vessel	v					v			
Limited shift duration according to working hours	v			v	v	v		v	v
Other constraints									
Spares and technician availability			v	v	v	v	v		
Accessibility related to weather conditions				v		v	v	v	v
Accessibility specified per unit/ task				v	v	v		v	v
Cost in objective									
Downtime cost calculated with weather data				v		v			v
Downtime cost specified per maintenance task				v		v			v
Penalty cost for delaying a task to another time period	v	v			v	v	v		
Travel cost	v	v	v	v	v	v	v	v	v
Number of ticks	11	11	10	13	13	20	13	16	16

Figure 3.2: Summary of published maintenance support vessel schedule and routing problem formulations for offshore wind farms

3.3. General description solution methods

When the routing and scheduling problem is formulated properly a solution method is required to solve the problem and find the optimal or near-optimal solution. This section explains what a solution method is and what types of methods are developed.

A significant number of research is conducted to solve all forms of vehicle routing problems. The solution methods can be divided in exact methods, classical heuristics, and meta-heuristics. The choice of solution method is generally based on the required calculation time and the accuracy of the solution. Furthermore, simplicity of implementation and flexibility in terms of applicability of the method are considered [67]. The solution method types and their advantages and disadvantages are described in this section.

3.3.1. Exact methods

An exact solution method finds the provable optimal solution to an optimisation problem. A commonly used exact solution method is the Branch-and-Bound method. It forms the framework for almost all commercial software for solving mixed integer programming problems [68]. The method has a ”divide and conquer” approach. It divides the set of solutions into several mutually exclusive subsets. Then it finds a lower bound on the optimal value of the solutions in the subsets. If the lower bound is higher then the current solution, the entire subset is skipped. These steps are repeated until no better solution can be found. For more information on exact solution methods for the VRP the reader is referred to the extensive survey written by Laporte et al. [68].

Exact solution methods generally do not scale well. The computation time increases substantially for problems of a larger scale. Even for medium sized problems (containing several hundreds of customers) the computation time of an exact solution method is generally not acceptable in real-word applications. Pecin et al. [69] have showed that even with a state of the art Branch-and-Bound method it takes multiple hours to solve problems with only 360 customers. However, for problems with tight constraints that reduce the number of possible solutions exact methods can solve the problem within seconds [70].

3.3.2. Classical heuristics

Because the computational time of exact methods is often not acceptable in practice, heuristics are introduced. A heuristic is an approach which does not guarantee the achievement of an optimal solution but is sufficient for reaching an immediate goal [71]. For VRPs it finds the best possible solution, according to a certain objective, within a given amount of computation time. Heuristics for VRPs consist of route construction and route improvement.

Route construction heuristics are used to create an initial solution to a VRP. It constructs an initial route between the customers. The most widely known construction heuristic is the Clarke and Wright savings algorithm [72]. It is applicable for VRP where the number of vehicles is a decision variable and for directed as well as undirected problems. It first computes the savings when merging back and forth routes between the depot and a customer (see figure 3.3). It creates n routes and orders the savings in a non-increasing fashion. For the parallel version of the algorithm, the merge yielding the largest saving is implemented. For the sequential version, the route is extended until there is no feasible route merge left. An other well known classical heuristics is the sweep algorithm [73]. It applies to planar variants of the VRP. First, feasible clusters are formed by rotating a ray over a certain angle with the depot as centre. For each cluster a route is obtained by solving the TSP (Travelling Salesman Problem). The solution is optimized by exchanging vertices between adjacent clusters and re-optimizing the cluster routes.

Above explained heuristics include route construction and route optimization. Moreover, there are also heuristics developed that only focus on route optimization called improvement heuristics. Improvement heuristics for the VRP contain variants that work on each vehicle route separately and variants that work on several routes at the same time. If each vehicle route is improved separately, any improvement heuristics for the TSP can be applied. Most improvement heuristics for the TSP are based

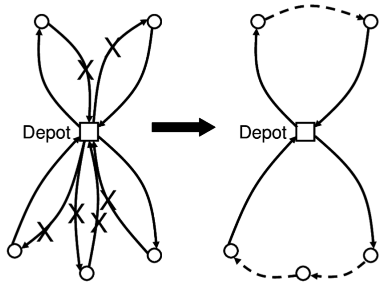


Figure 3.3: Representation of the saving algorithm [74]

on Lin's [75] λ-opt mechanism. The λ-opt mechanism removes λ edges of an existing feasible tour and connects the remaining segments with λ edges that are not in that solution. The edges are only exchanged when it results in a "better" tour. How "better" is defined depends on the objective function of the problem. The procedure continues until no further improvements can be obtained. If that is the case, the solution is λ-optimal. A (λ+1)-optimal solution is better than a λ-optimal solution, but requires more computation time. For the VRP, improvement heuristics consist of multi-route edges exchanges. Where multiple edges are exchanged between a variable number of routes until the local optimum is achieved. [76]

The downside of classical heuristics is the result of not allowing the intermediate solution to deteriorate. This causes that the process often gets trapped in a local optimum [77]. For more information on classical heuristics for the VRP the reader is referred to the survey written by Laporte et al.[76].

3.3.3. Meta-heuristics

Compared to classical heuristics, meta-heuristics perform a much more thorough search of the solution space. Since meta-heuristics allow less optimal moves and recombinations of solutions to create new ones, they are less likely to get stuck on a local optimum [67]. The most well known meta-heuristics are simulated annealing, deterministic annealing, Tabu search, genetic algorithms, ant systems, and neural networks.

Tabu search [78] stands out as the best meta-heuristic for the VRP compared to the others named above [67]. Figure 3.4 show a general flowchart of the Tabu search algorithm. The Tabu search performs a local search by moving from a solution x_t to the best solution $x_(t+1)$ in its neighborhood at each iteration t. The algorithm allows iterations that may cause the objective function to deteriorate. An anti-cycling mechanism is included that forbids, for a number of iterations, any solution possessing some attribute of x_t. Recently examined solutions are declared *tabu*. The stopping criteria is based on a chosen maximum number of iterations after the best solution has been found. [76][79]

Simulated annealing [81] as well as Tabu search works according to the local search principle and guides the search procedure beyond local optimality. It avoids cycling by accepting non-improvement moves with certain probabilities. These probabilities are defined by a control parameter (T), called temperature. The temperature is allocated according to a deterministic cooling schedule. The cooling schedule divides a temperature range over the number of feasible exchanges according to the minimum and maximum change in the objective function. The algorithm terminated when a chosen number of iterations are performed after the best solution has been found. [79]

Deterministic annealing was first proposed by Rose et al. [82] and is a deterministic variant of simulated annealing. Simulated annealing searches the minimum stochastically at each temperature while decreasing the temperature. Deterministic annealing searches the minimum deterministically at each temperature. While simulated annealing is a approximation method and theoretically can find the optimal solution, deterministic annealing can not guarantee to find the optimal solutions. If multiple local minima exist for a certain temperature it might not be able to find the overall minimum. However, deterministic annealing consumes less computation time because of its deterministic search method. [83]

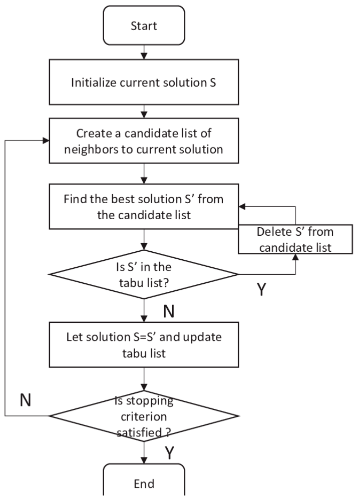


Figure 3.4: General flowchart of tabu search algorithm [80]

Genetic algorithm (GA) is a meta-heuristic that has several applications in VRPs including time windows. In genetic algorithms, each solution is imagined as a population member with genes. The genes represent the proporties of the solution. For example, for a VRP with one vehicle and n locations, a solution is a sequence of n genes indicating the order in the range $[1, n]$ of the locations in the route. First, an initial population of solutions or individuals is generated randomly. Then the evolution of the population starts with the first iteration. Each iteration is called a generation. In each iteration the previous generation is evaluated on the basis of the value of the objective function which represents their fitness. The more fit solutions or individuals are selected stochastically and their genes are modified to form the new generation. The new generation is again evaluated to continue the evolution. The algorithm generally stops running when either a maximum number of generations is formed or a satisfactory fitness level has been reached for the population. [84]

The ant system (AS) algorithm is introduced by Colorni et al. [85] and initially used to solve the TSP (Travelling Salesman Problem). It is based on the behaviour of ant colonies. Ants communicate information about food sources through an aromatic essence called pheromone which they place in a quantity that represents the quality of the food source discovered. Other ants follow the pheromone trail and reinforce it on their way back when they have found food indeed (see figure 3.5). If a trail is not enforced the pheromone evaporates. With the ant system algorithm for VRPs artificial ants successively visit customers until each customer is visited. Whenever the visit of a next customer leads to an infeasible path according to the problem constraints, the ant returns to the depot and starts over. The paths found by each ant are compared and the ”pheromone” level of each edge between two customers is updated which represents the quality of the edge. For the next iteration the ants follow the ”pheromone” and construct a new solution. [86]

Neural network algorithms are most commonly used in machine learning. It is based on a biological neural networks that form animal brains. It consists of an input layer and an output layer with in between multiple hidden layers. The layers consist of many neurons (nodes) which are connected with synaptic links (weights). So each neuron at a layer has a link with a number of neurons from the previous layer [88]. Neural network applications to the VRP have been rather unsuccessful [56].

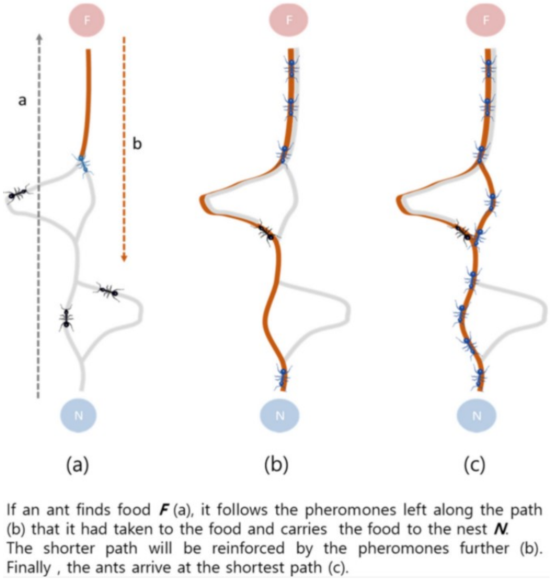


Figure 3.5: Ant system representation [87]

3.4. Solution methods for routing and scheduling of offshore wind farms

As not all solution methods are applicable for all sorts of VRPs, it is useful to understand the solution methods that are developed to solve a similar problem. The formulation of the maintenance support vessel routing and scheduling problem for an OWSF in this study is based on a mathematical formulation developed for offshore wind farms. Therefore, this section explains the solution methods developed for the maintenance support vessel routing and scheduling of offshore wind farm maintenance.

To the authors knowledge Zhang [28] was the first to propose a solution method to solve the maintenance support vessel routing and scheduling problem of offshore wind farms. He proposed a modified Ant Colony Optimization (ACO) named Duo-ACO. The ACO or ant system (AS) algorithm is described in previous section. The Duo-ACO works according to the same principle but has two groups with the same number of ants. Each ant group has its own pheromone. With each iteration an ant from both groups with the same index selects nodes successively according to their probabilities. When both ants have visited all nodes the pheromones are similarly updated for the two groups, pheromone is appointed to the node that is selected by the ant. Then the ants with the next index of both groups visit all nodes. When all ants have visited all nodes the iteration number increases one by one until a maximum number of iterations. Then the routes with the same index and the most pheromone for each group form the solution. The study showed that the solution method can solve the problem effectively. However, when stochastic constraints are included in the model a more robust method should be considered. A stochastic constraint includes a variable that is determined by a probability function. For instance a customer demand that has a value with a specified probability.

As stated earlier in this chapter Stålhane et al. [34] modeled the problem as a path-flow model. For path generation the labelling algorithm is used. The labelling algorithm uses two sets of labels, the set U of unprocessed labels and the set P of processed labels. Initially U contains only the label of the path just leaving the origin (the depot) and set P is empty. The path with the label that has spend the least amount of time in U is extended along all feasible arcs creating new labels L'. If the new label L' not dominated by any other label, it is added to U and P. The labels in P that are dominated by L' are removed from both P and U. When there are no unprocessed labels left in U the labels in P are filtered out. The paths of which the last node is not equal to the supposed end-node and return the remaining labels in P to U which may be converted into feasible non-dominated paths. The proposed labelling algorithm for the path-flow model solves the problem near optimality at a smaller computational time than the proposed exact method.

Irawan et al. [32] developed an algorithm to solve the routing and scheduling problem of offshore wind farms that is based on the Dantzig-Wolfe decomposition method. A mixed integer linear program is solved for each subset of turbines. This generates all feasible routes and schedules for the vessels for each period. The an integer linear program finds the optimal route and schedule configuration. This solution method is also called priori column generation. The model of Irawan et al. obtained the optimal solutions in a smaller computational time then the approach of Dai et al. with a commercial exact solution algorithm. However, for larger wind farms and clusters of wind farms a exploration of meta-heuristics is recommended.

Raknes et al. [6] developed two different rolling horizon heuristics to solve the large instances of the model where commercial mixed integer programming (MIP) solvers have too much running time. Rolling horizon heuristics generate iteratively solutions to MIPs. It divides the planning horizon into sub-horizons. Each sub-horizon is split into one detailed time block (DTB) and one aggregate time block (ATB) (see figure 3.6). The first block of the sub-horizon, DTB, is modelled in detail. The rest of the sub-horizon, ATB, is simplified according to the simplification strategy. The ATB is represented in an aggregate manner in order to evaluate the impact of future available capacity when including it in the DTB. Some or all of the decisions made for the DTB are fixed according to the specified fixing strategy. The fixed decisions remain fixed for all following iterations. For the next iteration the DTB is expanded with a specified number of time periods and the ATB is shifted towards the end of the planning horizon with an equal number of time periods. The algorithm stops running when the entire planning period is included in the DTB. The two proposed rolling horizon heuristics differ in the the fixing strategy. Raknes et al. added symmetry breaking constraints to the model to reduce the symmetry. Symmetry increases the size of the search space and therefore increase the computational time. Since the rolling horizon heuristic only searches for the optimal solution for the given horizon, it is not guaranteed that this solution is the optimal solution over the entire planning period. The rolling horizon method is better applicable when considering a static situation over a fixed time horizon. When evaluating the problem in a dynamic setting (with varying input) the direct solution of the full model over a limited planning horizon gives better results.

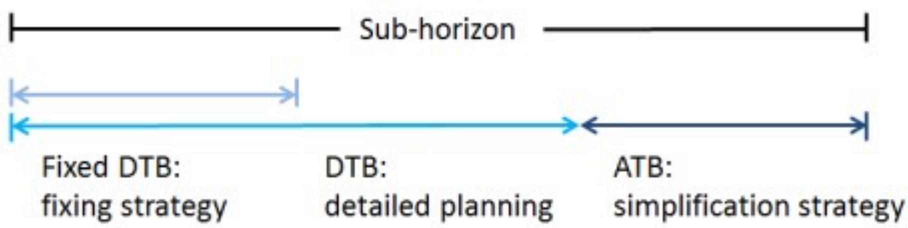


Figure 3.6: Illustration of the fixed detailed time block (DTB), the free DTB and the aggregate time block (ATB) of a general rolling horizon heuristic. [6]

A Two-Stage Adaptive Large Neighborhood Search (2-ALNS) heuristic is developed by Schrotenboer et al. [33] to solve the introduced Technician Allocation and Routing Problem (TARP) for offshore wind farms. The Adaptive Large Neighborhood Search (ALNS) is a meta-heuristic first introduced by Ropke and Pisinger [89]. The ALNS algorithm removes at each ”move” parts from the solution with destroy operators and inserts removed parts back in the solution with repair operators. With each move independently selected destroy and repair operators are applied. The probability of selecting the operators depends on the success of previous moves, the probability of the corresponding operators is increased after a successful move. The iterative destroying and repairing of the solution is embedded in a simulated annealing environment. The number of iterations and the difference in objective value determine the probability of the acceptance of a move. The procedure terminates after a fixed number of iterations. The ALNS procedure is applied in a two- stage procedure. In the first stage, it starts with ten initial solutions and performs on each initial solution a single run. In the second stage, the four best solutions are selected from the first stage procedure. Those four solutions are improved with the ALNS algorithm including a shaking procedure. The shaking procedure copes with the dependency between the allocation of technicians and the optimization of the routes what increases the difficulty of escaping the local optima. The 2-ALNS provides often optimal solutions on proposed problem formulations from the literature. The heuristic is also applicable for models that incorporate stochastic travel times and weather conditions.

Another research conducted by Stock-Williams and Swamy [35] applied a Genetic Algorithm (GA) to solve the daily maintenance planning problem. Figure 3.7 presents the process of one iteration in the solution method developed by Stock-Williams et al.. As explained in the previous section solutions to the problem are considered as a population in GA. Each population member 'Individual' has its unique genes that represent the value of the variables for that solution. New Individuals are generated either randomly or through "cross-over" and "mutation" operators to form the new generation from selected Individuals. Each proposed solution is transformed into a real world representation of the problem the 'Transfer Plan', often with additional information or assumptions. The Transfer Plan is evaluated against the optimization objective(s) in order to determine the performance indicators. The evaluation is performed by means of a detailed simulation of the current day according to the proposed solution. The performance indicators are provided back to the GA, and determine the fitness of the proposed solutions. Then the current population is updated according to the fitness of all Individuals and the new iteration starts. This heuristic is designed to be applicable for an optimisation-simulation model, therefore the optimisation is simplified as the simulation incorporates a part of the constraints.

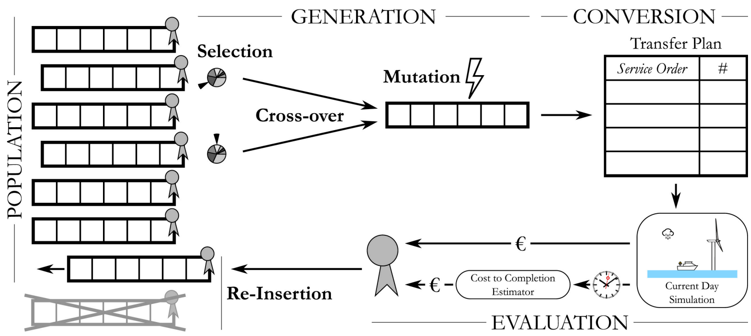


Figure 3.7: The process involved in completing one iteration of a Genetic Algorithm search as implemented in the solving algorithm of Stock-Williams et al. [35].

A hybrid heuristic optimization is proposed by Fan et al. [37] to solve the maintenance routing and scheduling problem of offshore wind farms. The optimization problem is divided into two parts. The first part establishes the mapping relationship between the maintenance bases and the involved wind farms and determines the number of wind farms that will be serviced by the vessel. The second part uses the scheme of vessel allocation to optimize the maintenance route (see figure 3.8). A modification of the traditional particle swarm optimization (PSO) is proposed named mixed PSO (MPSO) that represents the first part. The PSO considers the potential solutions to the problem as a swarm of particles. Each particle has a state, which consists of the solution parameters. The particles have a velocity and a position at each iteration that are constructed from their own best-known position in the search-space and the entire swarm's best-known position. Each iteration the velocity and the position of the particle is updated according to the updated best-known positions. If the new position of a particle is beyond the solution space, the iteration of that particle stops. Otherwise, the iteration stops when it reaches the maximum number of iterations. The second part of the optimization method is a discrete wolf pack search (DWPS) . The original wolf pack search algorithm is inspired by the social hierarchy and hunting behaviour of wolves in nature. The DWPS is a proposed variant by Fan et al. of the original algorithm to make it suitable for an integer programming problem with complex constraints like the routing problem of offshore wind farms. The allocation of the vessels is determined in part 1. The potential solutions for the routing of the vessels are considered as a pack of wolves. The wolves have a fitness which is calculated with the objective function, the wolf with the highest fitness is the leading wolf. The other wolves are the searching wolves and search in the solution space for a better solution. The better solution is constructed from a switch in the sequence of turbine visits. When the maximum number of iterations is reached or a new leader wolf is found. All wolves except for the leading wolf become the summoned wolves. The leading wolf shares its experience i.e. the dominant sequence of turbine visits with the summoned wolves. When a new leading wolf with a better fitness or a maximum number of cycles is reached, the wolves except for the leader become the sieging wolves. The sieging wolves are compared with the leader wolf and the wolves are adjusted such that the solutions become closer to the leading solution. When a more fit wolf is found or the maximum number of iterations is reached all steps are executed and the fitness function is calculated for all artificial wolves. The most fit wolf represents the optimized solution and is the output of the algorithm. The proposed method is compared to the method of Zhang [28]. It appears that the method of Fan et al. is applicable to a larger wind farms and more realistic constraints. However, the optimal solution is not guaranteed as it is a heuristic approach.

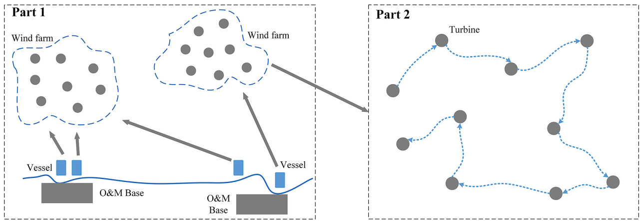


Figure 3.8: A representation of the two parts of the hybrid heuristic optimization by Fan et al. [37]

Lazakis and Khan [36] developed an optimization framework for daily route planning and scheduling of maintenance vessel activities in offshore wind farms. As described in section 3.2 Lazakis and Khan divided the problem in two sessions; drop-off and pick-up session. The optimization method consists of multiple algorithms that are consecutive implemented. Algorithm 1 first checks if the weather conditions of planning period (one day) meet the vessels limitations. Then it starts planning the drop-off session. Which turbines need maintenance that day is given. The solution method is not build up like conventional optimization methods. It does not find the optimal solution in a solution space but it builds a solution according to formulated building steps. At first the sequence of the turbine visits is based on minimum travelling distance for both the drop-off and pick-up session. If the total time to complete the maintenance tasks exceeds the available time window related to the weather and maximum working hours, a different heuristic strategy is applied. This algorithm sorts the remaining maintenance requiring turbines based on distance from the initial SOV location. The first turbine in the ranking is inserted in algorithm 1. If the total time to complete all maintenance tasks still exceeds the available time window, the second turbine is inserted in algorithm 1. If a turbine is found that does not exceed the remaining time of the time window, it is added the sequence. If all maintenance requiring turbines are added to the sequence or no time is left the process stops running. The operational planning of the CTVs is executed with a similar process. If multiple vessels are available, the turbines that need maintenance are first clustered. The computational time to perform optimization for all the test cases with 91 turbines was less than a minute. However, this method does not guarantee the optimal solution as it does not evaluate all feasible solutions.

The multi-agent based simulation-optimization for offshore wind farm maintenance of allal et al [51] includes a meta heuristic based on the Ant Colony System (ACS). ACS differs from the earlier explained AS in three main aspects. ACS applies a more aggressive action choice rule. Only to arcs belonging to the global-best solution pheromone is added. And each time an ant moves along an arc, it removes some pheromone from the arc. The simulation-optimization consist of multiple agents so that each component of the complex system can be treated individually. The agent "Monitoring" ensures the co-ordination of the launch of maintenance and establishment of tour plans and launches the ACS. When it appears that a turbine needs maintenance during the simulation, the ACS is used to find the best route while taking the state of the other wind turbines, the date of their next maintenance and the necessary distance to perform a tour into account. It selects a set of wind turbines to maintain during the same tour as the one selected before while minimizing the cost. The heuristic proposed in this research is simplified as it is part of a simulation-optimization method. Therefore, it is not separately applicable to large routing and scheduling problems. The simulation should be run multiple times to find the optimal solution as not all aspects are evaluated by the optimization agent, this is very time consuming.

In addition to self developed heuristics algorithms, commercial optimizers are used to solve the maintenance support vessel routing and scheduling problem for offshore wind farms. Dai et al. [29] solved the optimization problem with the Xpress Optimizer that applies an exact solution method. Tan et al. [66] uses Gurobi for solving the optimization problem of scheduling short term maintenance for offshore wind farms. The Gurobi Mixed-Integer Programming solver utilizes an advanced pioneering Branch-and-Cut algorithm. The Branch-and-Cut solution method is a combination of the commonly used Branch-and-Bound method (explained in section 3.3.1) and the cutting-planes method [68]. The algorithm relaxes the problem by only considering a number of constraints. Then it divides the set of solutions into several mutually exclusive subsets. With introducing the rest of the constraints is cuts off subsets that do not comply with the introduced constraint.

3.5. The most applicable method

The applicable method for optimization of routing and scheduling maintenance support vessels for an OWSF consists of a mathematical formulation and a solution method. Subsection 3.5.1 describes the selection of the most applicable mathematical formulation and subsection 3.5.2 describes the choice for a solution method.

3.5.1. Mathematical formulation

Chapter 2 lists the requirements for an optimization model for the routing and scheduling of maintenance support vessels of an OWSF. The different mathematical formulations in the literature for offshore wind farms are assessed on which requirements for an OWSF are included (See figure 3.9).

	Dai et al. (2015) [28]	Stålhane et al. (2015) [34]	Dawid et al. (2016) [63]	Tan et al. (2017) [64]	Irawan et al. (2017) [31]	Raknes et al. (2017) [32]	Schrotenboer et al. (2018) [33]	Lazakis et al. (2021) [36]	Allal et al. (2021) [49]
Maintenance tasks are allocated to different nodes	v	v	v		v	v		v	v
Multiple vessels with different routes	v	v	v	v	v	v	v	v	v
Different characteristics for vessels						v	v	v	
Multiple services orders per tour			v	v				v	v
Downtime cost related to the maintenance task				v		v			v
Downtime cost related to weather conditions				v		v			v
Distinction between preventive and corrective maintenance tasks	v				v	v	v	v	
number of ticks	3	2	3	4	3	6	3	5	5

Figure 3.9: Assessment of the mathematical formulations

The mathematical problem formulated in the research of Raknes et al. [6] includes most of the requirements for representing the maintenance support vessel routing and scheduling problem for OWSFs.

3.5.2. Solution method

When the mathematical representation of the problem is formulated a solution method is applied to find the optimal solution. Figure 3.10 gives an overview of the described solution methods applied to offshore wind farm vessel routing and scheduling problems. Exact methods provide an 100 percent accurate solution but require more computational time than meta-heuristics solution methods. Meta-heuristic solution methods provide less accurate solutions. They exist of complex mathematical algorithms, and are therefore harder to apply. Accuracy and applicability are important as the research aims for an accurate solution and the solution method should be applicable for solving the chosen mathematical formulation of the optimization problem. The chosen mathematical formulation is based on mixed integer programming (MIP) with an extensive number of constraints. Gurobi is proven to be an effective commercial mixed integer programming (MIP) applicable for a wide range of routing and scheduling problems and easy to implement. Therefore, Gurobi is chosen as solution method for this research.

	Zhang (2014) [27]	Stalhane et al. (2015) [34]	Irawan et al. (2017) [31]	Raknes et al. (2017) [32]	Schrotenboer et al. (2018) [33]	Stock-Williams and Swamy (2019) [35]	Fan et al. (2019) [37]	Lazakis et al. (2021) [35]	Allal et al. (2021) [49]	Gurobi
Solution method (Exact (E)/ Meta-heuristics (M))	M	M	E	E	M	M	M	M	M	E
Method	Duo-ACO	Labelling	Dantzig-Wolfe decomposition	Rolling horizon heuristics	2-ALNS	GA	MPSO + DWPs	Multiple consecutive unconventional heustics	ACS	Branch-and-cut algorithm

Figure 3.10: Summary of solution methods applied for maintenance support vessel routing and scheduling for offshore wind farms

4
Adjustment of the mathematical formulation

In the previous chapter is concluded that the mathematical formulation of Raknes et al. [6] a sufficient base is for the mathematical model to optimize the maintenance support vessel routing and scheduling for an offshore wind and solar farm. However, multiple adjustments are to be made. This chapter presents and explains the adjustments that are implemented to make the model applicable for an offshore wind and solar farm. With that, it answers the sub-question *Is the chosen optimization method fully applicable for route and schedule optimization of maintenance support vessel of an OWSF, if not which adjustments are required?*. Section 4.1 presents the model of Raknes et al., section 4.2 explains the main adjustments and section 4.3 presents the adjusted mathematical problem.

4.1. The model of Raknes et al.

The mathematical model of Raknes et al. [6] is formulated for the maintenance support of multiple wind farms from one depot. It is a static and deterministic routing and scheduling problem for a short planning period formulated as a mixed integer programming (MIP) model. The planning period exists of multiple shifts. One shift represents a working day of 8 hours. The routing in the model consists of two levels. The first level is the routing of the vessels between wind farms and the depot and the second level is the routing of vessels within the wind farm. The routing between wind farms is considered as a graph where each wind farm is represented by one node and the depot by two nodes; a start and an end node. In the graph, the arcs between the nodes are associated to travelling times and travelling costs. The second level, the routing between wind turbines, is not considered as a graph. The turbines that require maintenance are represented by the maintenance tasks and the location of the turbines are ignored. The average travel time between the turbines in the wind farm is added to the task duration. The maintenance tasks consist of delivery tasks and pick-up tasks, which represent the drop-off and pick-up of technicians by the vessel. The model includes a target amount of performed preventive maintenance tasks in the planning period. Furthermore, the model makes distinction between performed tasks and completed tasks. A performed task in a shift is executed but not completed during the shift. A completed task is finished during that shift. The model incorporates SOV's, called an accommodation vessel (AV) in the model, that can stay at the wind farm for multiple shifts and CTV's that depart from the depot at the start of a shift when the weather conditions allow it. Figure 4.1 shows a representation of the routing and scheduling model of Raknes et al.

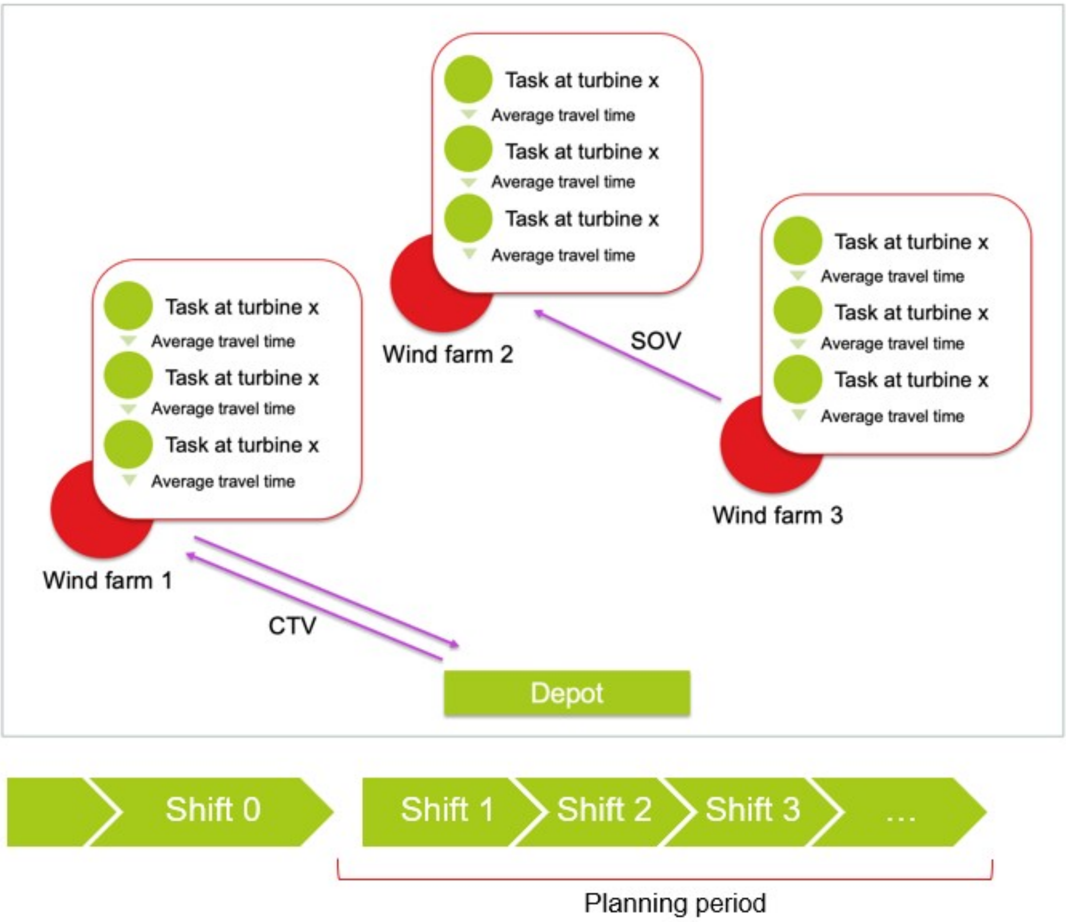


Figure 4.1: Representation of the routing and schedling model of Raknes et al.

The mathematical model is solved with a rolling horizon. Therefore, the model is developed to review one planning period with a few shifts for the optimization. It only considers the last shift of the previous planning period to meet certain time constraints, but the optimization is focused only on one period with a number of corrective maintenance tasks and a desired number of preventive maintenance tasks to be completed.

The mathematical formulation of Raknes et al. is presented and explained beneath.

Indices

i, j	Nodes (wind farms and depot)
m, n, l	Maintenance tasks
k	Type of maintenance tasks
v	Vessels
s	Shifts

Sets

N^W	All wind farm nodes, $N^W = \{1, 2..., \lvert N^W\rvert\}, N^W \subset N$
N	All nodes, $N = \{0, 1, 2, ..., (\lvert N^W\rvert + 1)\}$. Nodes $i \in \{1, 2, ..., \lvert N^W\rvert\}$ are wind farms and nodes $i \in \{0, (\lvert N^W\rvert + 1)\}$ represent the depot
K	All maintenance task types
M	All maintenance tasks including both delivery tasks and pick-up tasks, $M = \{0, 1, 2, ..., \lvert M\rvert\}$
M^-	All delivery tasks (representing the actual maintenance tasks), $M^- = \{1, 2, ..., \lvert M^-\rvert\}, M^- \subset M$
M_i^-	All delivery tasks at wind farm i, $i \in N^W, M_i^- \subseteq M^-$
M_{ik}^-	All delivery tasks of type k at wind farm i, $i \in N^W, k \in K, M_{ik}^- \subseteq M_i^-$
M^+	All pick-up tasks $M^+ = \{(\lvert M^-\rvert + 1), (\lvert M^-\rvert + 2), ..., (2\lvert M^-\rvert)\}, M^+ \subset M$
M_i^+	All pick-up tasks at wind farm $i, i \in N^W, M_i^+ \subseteq M^+$
M^C	All corrective maintenance tasks, $M^C \subseteq M^-$
M^P	All preventive maintenance tasks, $M^P \subseteq M^-$
V	All vessels
V^A	All AVs, $V^A \subseteq V$
V^C	All CTVs, $V^C \subseteq V$
V_m	All vessels that can perform maintenance task $m, V_m \subseteq V$
V_m^A	All AVs that can perform maintenance task $m, V_m^A = V_m \cap V^A$
V_m^C	All CTVs that can perform maintenance task $m, V_m^C = V_m \cap V^C$
S	All shifts of the planning period
S^0	All shifts of the planning period, including the last shift of the previous planning period, shift 0

Constants

T_{ijv}^T	Transportation time between node $i \in N$ and node $j \in N$ for vessel $\in V$
T_m^{MT}	Duration of task $m \in M^-$
T^{PD}	Time to transfer technicians from vessel to turbine and from turbine to vessel (transfer time)
T_{iv}^{IT}	Average time to travel between turbines in wind farm $i \in N^W$ for vessel $v \in V$
D_v^{START}	Number of shifts a vessel $v \in V^A$ has been offshore when the planning period starts
D_v^{LIMIT}	Number of shifts a vessel $v \in V^A$ can stay offshore without returning to the depot
P_{iv}^{START}	1 if vessel $v \in V^A$ is located at node $i \in N$ at the start of the planning period, 0 otherwise
T^{DAY}	Number of time units in a day
T_s^{SHIFT}	Length of shift $s \in S$
T^{MIN}	Minimum length of weather window in a shift for a CTV to leave the depot during the shift
L_{vs}^W	Lower bound for the weather window of vessel $v \in V$ in shift $s \in S$
U_{vs}^W	Upper bound for the weather window of vessel $v \in V$ in shift $s \in S$
B	The desired number of preventive maintenance tasks to be completed during the planning period
R_{ms}	1 if all necessary spare parts and equipment for performing task $m \in M^-$ are available in shift $s \in S$, 0 otherwise
E_m	1 if task m requires that the vessel performing the task is located at the turbine while the task is being performed, 0 otherwise
Q_v	Technician capacity of vessel $v \in V$
P_m	Number of technicians needed to perform task $m \in M$, positive for delivery tasks and negative for pick-up tasks
C_{ijv}^T	Transportation costs between node $i \in N$ and node $j \in N$ for vessel $v \in V$
C_{ms}^{LP}	Downtime costs per time unit during shift $s \in S$ due to loss of production when shutting down the turbine where maintenance task $m \in M^-$ is located
C_v^{OUT}	The cost for vessel $v \in V^A$ to stay offshore between two shifts
C_v^{IT}	The average internal transportation cost for vessel $v \in V$ to travel to a maintenance task $m \in M^-$ inside a wind farm
C_m^{NP}	The penalty cost per shift of not completing a preventive maintenance task during the planning period
C_m^{NC}	The penalty cost per shift of not completing a corrective maintenance task during the planning period

C_m^{NP*} The penalty cost per time unit of remaining work for a preventive maintenance task $m \in M^P$ that is not completed within the planning period

C_m^{NC*} The penalty cost per time unit of remaining work for a corrective maintenance task $m \in M^C$ that is not completed within the planning period

K_{ms} 1 if the energy production during shift $s \in S$ is below a specified limit for when to perform $m \in M^- \cap M^P$ as extra preventive maintenance, 0 otherwise

δ Small value greater than zero

Decision variables

x_{mvs} 1 if vessel $v \in V_m$ is used to perform maintenance task $m \in M$ during shift $s \in S$, 0 otherwise

y_{ijvs} 1 if vessel $v \in V$ travels directly between node $i \in N$ and $j \in N, i \neq j$, during shift $s \in S$, 0 otherwise

z_{mnvs} 1 if vessel $v \in V_m \cap V_n$ performs maintenance task $n \in M$ directly after maintenance task $m \in M$ during shift $s \in S$, 0 otherwise

w_{ivs} 1 if vessel $v \in V^A$ stays at node $i \in N$ between shift $s \in S$ and $(s+1) \in S$, 0 otherwise

t_{mvs} The time vessel $v \in V_m$ starts maintenance task $m \in M$ during shift $s \in S$

l_{ms} Time counter for how long the turbine where maintenance task $m \in M^-$ is located is shut down during shift $s \in S$. The time counter for shift s starts at 0 when the shift starts and reaches its maximum at the beginning of the next shift, $s+1$

c_m The penalty cost of a task $m \in M^-$ that is not completed during the planning period

p_{mvs} The number of technicians at vessel $v \in V_m$ immediately after visiting the turbine of task $m \in M$ during shift $s \in S$

f_{ms} 1 if task $m \in M^-$ is completed before the end of shift $s \in S$ (during shift s or during earlier shifts than s), 0 otherwise

Objective function

$$\min Z = \sum_{i \in N} \sum_{j \in N} \sum_{v \in V} \sum_{s \in S} C_{ijv}^T y_{ijvs}, \tag{4.1a}$$

$$+ \sum_{m \in M^-} \sum_{v \in V_m} \sum_{s \in S} C_v^{IT} x_{mvs}, \tag{4.1b}$$

$$+ \sum_{i \in N^W} \sum_{v \in V_m} \sum_{s \in S} C_v^{OUT} w_{ivs}, \tag{4.1c}$$

$$+ \sum_{m \in M^-} \sum_{s \in S} C_{ms}^{LP} l_{ms}, \tag{4.1d}$$

$$+ \sum_{m \in M^P} \sum_{s \in S} C_m^{NP} (1 - f_{ms}), \tag{4.1e}$$

$$+ \sum_{m \in M^C} \sum_{s \in S} C_m^{NC} (1 - f_{ms}), \tag{4.1f}$$

$$+ \sum_{m \in M^-} c_m \tag{4.1g}$$

The objective function of the optimization problem minimizes the total cost. Transportation cost for the vessel between wind farms and the depot are included (see 4.1a). Sub-equation 4.1b considers the internal transport costs within a wind farm, based on the performed tasks and the average transportation time between turbines in the farm. AV's can stay offshore for multiple shifts, these costs are represented by 4.1c. During certain maintenance tasks it is required that the turbine is shut down. The production loss during shut down is taken into account as downtime cost in 4.1d and varies per shift according to the weather expectations. In addition to the real costs, penalty costs are included. Sub-equation 4.1e and 4.1f apply penalty costs for not completing a task during a shift for preventive and corrective tasks respectively. These parts of the objective function ensure that the respective tasks are completed within a shift if there is free vessel capacity. There is also an encouragement to work on tasks for which there is insufficient time to complete them during the planning period, if there is free vessel capacity. A penalty cost for each task that is not completed based on how much time there is left of the task at the end of the planning period is added in 4.1f.

The constraints of the routing and scheduling problem of Raknes et al. are grouped as it is grouped in [6]. It consists of constraints concerning flow of CTVs, flow of AVs, execution of tasks, time management, precedence of tasks, downtime, technicians balances and the domain of the decision variables.

Constraints for the flow of CTVs:

$$\sum_{j \in N} y_{0jvs} = 1, \qquad v \in V^C, s \in S \tag{4.2}$$

$$\sum_{i \in N} y_{i|N|vs} = 1, \qquad v \in V^C, s \in S \tag{4.3}$$

$$y_{0|N|vs} = 1, \qquad v \in V^C, s \in S | (U^W_{vs} - L^W_{vs}) < T^{MIN} \tag{4.4}$$

$$\sum_{i \in N} y_{ijvs} = \sum_{i \in N} y_{jivs}, \qquad j \in N^W, v \in V^C, s \in S \tag{4.5}$$

$$\sum_{i \in N} \sum_{j \in N} y_{ijvs} \leq 2, \qquad v \in V^C, s \in S \tag{4.6}$$

Constraint 4.2 ensures that each CTV leaves the start depot node,$i = 0$, during each shift. Constraint 4.3 makes sure that each CTV ends at the end depot node, $i = |N|$, during each shift. A CTV may not leave the depot during a shift where the weather window is shorter than a specified minimum duration. This is prevented by constraint 4.4 by forcing the CTV to go straight from beginning node to end node which represent both the same depot. Constraint 4.5 ensures that when a CTV visits a node it also leaves the node during the same shift. In the model of Raknes et al. CTVs can only visit one wind farm during a shift. Therefore, Constraint 4.6 restricts the CTV to travel only twice; to a wind farm and back form this wind farm to the depot.

Constraints for the flow of AVs:

$$w_{iv(s-1)} + \sum_{j \in N} y_{jivs} = \sum_{j \in N} y_{ijvs} + w_{ivs}, \qquad i \in N^W, v \in V^A, s \in S^0 \backslash \{0\} \tag{4.7}$$

$$\sum_{j \in N} y_{0jvs} = w_{|N|v(s-1)}, \qquad v \in V^A, s \in S^0 \backslash \{0\} \tag{4.8}$$

$$w_{|N|vs} = \sum_{j \in N} y_{j|N|vs}, \qquad v \in V^A, s \in S \tag{4.9}$$

$$\sum_{i \in N} \sum_{j \in N} y_{ijvs} \leq 1, \qquad v \in V^A, s \in S \tag{4.10}$$

$$w_{iv0} = P^{START}_{iv}, \qquad i \in N, v \in V^A \tag{4.11}$$

$$\sum_{i \in N^W} \sum_{s=1}^{D^{LIMIT}_v - D^{START}_v} y_{i|N|vs} \geq 1, \qquad v \in V^A | D^{LIMIT}_v - D^{START}_v \leq |S| \tag{4.12}$$

Because AVs are equipped to accommodate personnel for longer periods and can therefore stay offshore for multiple shifts, the node flow of AVs is differently handled. Constraint 4.7 ensures that an AV located at a wind farm at the beginning of a shift either leaves the wind farm at the end of the sift or stays there until the next shift. Constraint 4.8 handles that an AV can only leave the depot during a shift if it was located at the depot at the end of the previous shift. If the AV travels to the depot during a shift, constraint 4.9 makes sure that the AV stays at the depot until the next shift. Each AV is restricted by constraint 4.10 to performing no more than one trip during or prior to each shift. At the beginning of a planning period an AV can be located at a wind farm already according to P^{START}_{iv}. This is taken into account by constraint 4.11. The period an AV can stay offshore is limited by constraint 4.12.

Constraints for the execution of tasks:

$$\sum_{v \in V_m} x_{mvs} \leq 1, \qquad m \in M^-, s \in S \tag{4.13}$$

$$x_{mvs} = 1, \qquad v \in V^C, m = 0 \cup |M|, s \in S \tag{4.14}$$

$$x_{0vs} = w_{|N|v(s-1)}, \qquad v \in V^A, s \in S^0 | s > 0 \tag{4.15}$$

$$x_{|M|vs} = w_{|N|vs}, \qquad v \in V^A, s \in S \tag{4.16}$$

$$x_{mvs} \leq \sum_{j \in N} y_{jivs}, \qquad i \in N^W, m \in M_i^- \cup M_i^+, v \in V_m^C, s \in S \tag{4.17}$$

$$x_{mvs} \leq \sum_{j \in N} y_{jivs} + w_{iv(s-1)} - \sum_{j \in N} y_{ijvs}, \qquad i \in N^W, m \in M_i^- \cup M_i^+, v \in V_m^A, s \in S \tag{4.18}$$

Constraint 4.13 handles the requirement that each task is performed by maximum one vessel each shift. The CTVs start at the depot. Therefore, constraint 4.14 makes sure the depot tasks are performed by each CTV during each shift. AVs can start from an offshore location at one of the wind farms. For this reason, constraint 4.15 ensures that the start depot task is performed by an AV that is located at the depot and constraint 4.16 ensures the same for the end depot task. In the model of Raknes et al. the nodes represent the wind farms and the tasks of the wind turbines in the farm are associated with the wind farm node. Constraint 4.17 restricts that a task m at wind farm i can only be performed by CTV v if v is located at i during the shift. Constraint 4.18 concerns this restriction for AVs.

$$x_{mvs} = x_{(m+|M^-|)vs}, \qquad m \in M^-, v \in V_m, s \in S \tag{4.19}$$

$$\sum_{v \in V^m} x_{mvs} = 0, \qquad m \in M^-, s \in S | R_{ms} = 0 \tag{4.20}$$

$$\sum_{m \in M^P} \sum_{v \in V_m} x_{mvs} \leq B, \qquad s \in S | K_{ms} = 0 \tag{4.21}$$

A delivery and pick-up task at the same turbine must be performed by the same vessel. This is ensured by constraint 4.19. Constraint 4.20 prohibits performing a task during a shift for which $R_{ms} = 0$, which means that the task is not ready to be performed in that shift. In the model there is a desired number of preventive maintenance tasks to be performed per shift in addition to the corrective maintenance tasks. Extra preventive maintenance tasks can be performed if there is time or capacity left during the shift. However, constraint 4.21 makes sure that if the energy production is higher than a specified limit, the number of performed preventive tasks does not exceed the desired number of preventive tasks.

$$T_m^{MT} - \sum_{v \in V_m} \sum_{h=1}^{s} (t_{(m+|M^-|)vh} - t_{mvh} - T^{PD} x_{mvh}) + (T_s^{SHIFT} - T^{PD}) f_{ms} \geq \delta, \qquad m \in M^-, s \in S \tag{4.22}$$

$$\sum_{v \in V_m} \sum_{h=1}^{s} (t_{(m+|M^-|)vh} - t_{mvh} - T^{PD} x_{mvh}) \geq T_m^{MT} f_{ms} \qquad m \in M^-, s \in S \tag{4.23}$$

$$\sum_{v \in V_m} x_{mvs} \leq 1 - f_{m(s-1)}, \qquad m \in M^-, s \in S \setminus \{1\} \tag{4.24}$$

The constraints above (equation 4.22 till 4.24) handle the variables that indicate in which shifts each task is completed. f_{ms} becomes one by means of constraint 4.22 if task m is completed within shift s. f_{ms} is forced to zero by constraint 4.23 if task m is not completed within shift s. Constraint 4.24 restricts that a task m is executed during shift s after the task is completed.

$$c_m \geq C_m^{NC*}(T_m^{MT} - \sum_{v \in V_m} \sum_{s \in S} (t_{(m+|M^-|)vs} - t_{mvs} - T^{PD} x_{mvs})), \qquad m \in M^C \cap M^- \qquad (4.25)$$

$$c_m \geq C_m^{NP*}(T_m^{MT} - \sum_{v \in V_m} \sum_{s \in S} (t_{(m+|M^-|)vs} - t_{mvs} - T^{PD} x_{mvs})), \qquad m \in M^P \cap M^- \qquad (4.26)$$

Constraints 4.25 and 4.26 determine the penalty costs for uncompleted tasks according to the remaining required time for the task, for corrective and preventive tasks respectively. Both constraints are based on the difference between task duration and the time between the drop-off and pick-up tasks minus the transfer time. The remaining task time is multiplied by a cost per time unit for that particular task.

Constraints for time management

$$t_{mvs} \leq T_s^{SHIFT} x_{mvs}, \qquad m \in M, v \in V_m, s \in S \qquad (4.27)$$

$$t_{mvs} \geq L_{vs}^W \sum_{j \in N} y_{jivs} - T_s^{SHIFT}(1 - x_{mvs}), \qquad i \in N^W, m \in M_i^-, v \in V_m^C, s \in S \qquad (4.28)$$

$$t_{mvs} \geq \sum_{j \in N} T_{jiv}^T y_{jivs} - T_s^{SHIFT}(1 - x_{mvs}), \qquad i \in N^W, m \in M_i^-, v \in V_m^C, s \in S \qquad (4.29)$$

$$t_{mvs} \geq L_{vs}^W (\sum_{j \in N} y_{jivs} + w_{iv(s-1)}) - T_s^{SHIFT}(1 - x_{mvs}), \qquad i \in N^W, m \in M_i^-, v \in V_m^A, s \in S \qquad (4.30)$$

$$t_{mvs} \geq \sum_{j \in N^W} T_{0iv}^T y_{0ivs} - T_s^{SHIFT}(1 - x_{mvs}), \qquad i \in N^W, m \in M_i^-, v \in V_m^A, s \in S, \qquad (4.31)$$

$$t_{mvs} + T^{PD} x_{mvs} \leq U_{vs}^W, \qquad m \in M^+, v \in V_m, s \in S \qquad (4.32)$$

Constraint 4.27 ensures that the start time of task m is set to zero if the task is not performed. The start time of drop-off tasks must be greater than or equal to both the lower bound of the weather window and the travel time to the wind farm. This is taken care of by constraint 4.28 and 4.29 respectively. For AVs, constraint 4.30 ensures that start time of the drop-off tasks is greater than or equal to the lower bound of the weather window. The start time of drop-off tasks performed by an AV must be greater than or equal to the travel time from the depot to the wind farm is the AV starts the shift at the depot (see constraint 4.31). Constraint 4.32 makes sure that pick-up tasks start in time in order to be able to transfer the technicians before the upper bound of the weather window.

$$t_{(m+|M^-|)vs} \geq t_{mvs} + T^{PD} x_{mvs}, \qquad m \in M^-, v \in V_m, s \in S \qquad (4.33)$$

$$t_{mvs} - t_{nvs} + T_{iv}^{IT} + T^{PD} \leq T_s^{SHIFT}(1 - z_{mnvs}), \qquad i \in N^W, m \in M \backslash \{|M|\}, n \in M_i^- \cup M_i^+, v \in V_m \cap V_n, s \in S | m \neq n \qquad (4.34)$$

$$t_{mvs} - t_{|M|vs} + T^{PD} x_{mvs} + T_{i|n|v}^T y_{i|N|vs} \leq T_s^{SHIFT}(1 - z_{m|M|vs}), \qquad i \in N^W, m \in M_i^- \cup M_i^+, v \in V_m \cap V_n, s \in S \qquad (4.35)$$

The pick-up tasks should be performed after the drop-off task plus the transfer time. This is handled by constraint 4.33. The time between the start times of consecutive tasks must be greater than or equal to the sum of the average travel time between turbines and the transfer time (see constraint 4.34). Constraint 4.35 ensures that the time between the start times of the end depot task and the previous task must be greater than the sum of the transfer time and the travel time between the last wind farm and the depot.

Constraints for the precedence of tasks

$$x_{mvs} = \sum_{n \in M \setminus \{0\}} z_{mnvs} \qquad m \in M \setminus \{|M|\}, v \in V_m^C \cap V_n^C, s \in S \tag{4.36}$$

$$x_{mvs} = \sum_{n \in M \setminus \{|M|\}} z_{nmvs} \qquad m \in M \setminus \{|0|\}, v \in V_m^C \cap V_n^C, s \in S \tag{4.37}$$

$$x_{mvs} \geq \sum_{n \in M \setminus \{0\}} z_{mnvs} \qquad m \in M \setminus \{|M|\}, v \in V_m^A \cap V_n^A, s \in S \tag{4.38}$$

$$x_{mvs} \geq \sum_{n \in M \setminus \{|M|\}} z_{nmvs} \qquad m \in M \setminus \{|0|\}, v \in V_m^A \cap V_n^A, s \in S \tag{4.39}$$

$$\sum_{m \in M \setminus \{|M|\}} \sum_{n \in M \setminus \{0\}} z_{mnvs} \geq \sum_{m \in M} x_{mvs} - 1, \qquad v \in V_m^A \cap V_n^A, s \in S \tag{4.40}$$

$$z_{mnvs} = x_{mvs}, \qquad m \in M^-, n = m + |M^-|, v \in V_m, s \in S | E_m = 1 \tag{4.41}$$

For the precedence of tasks performed by CTVs, constraints 4.36 and 4.37 make sure that each task has a previous and a following task except for the depot tasks. Constraints 4.38 and 4.39 ensure that the tasks performed by AVs have maximum one previous and and one following task except for the depot tasks. As an AV can stay offshore, the first or last maintenance tasks at wind farms do not have a previous or following task if the AV stayed or stays offshore respectively. To make sure that the rest of the tasks do have a previous and following task constraint 4.40 states that the number of consecutive tasks must be minimal as much as the number of performed tasks minus one. Constraint 4.41 prevents vessels from leaving the turbine during a task that requires the vessel to stay, by forcing the pick-up task to be subsequent to the drop-off task.

Constraints for the downtime

$$l_{ms} \geq T^{DAY}(1 - f_{ms}), \qquad m \in M^C, s \in S \tag{4.42}$$

$$l_{ms} \geq \sum_{v \in V_m} (t_{(m+|M^-|)vs} + T^{PD} x_{mvs}) - T_S^{SHIFT}(1 - (f_{ms} - f_{m(s-1)})), \qquad m \in M^C, s \in S \setminus \{1\} \tag{4.43}$$

$$l_{ms} \geq \sum_{v \in V_m} (t_{(m+|M^-|)vs} + T^{PD} x_{mvs}) - T_S^{SHIFT}(1 - f_{ms}), \qquad m \in M^C, s = 1 \tag{4.44}$$

For corrective tasks the downtime starts at the beginning of the planning period. If the task is not performed during a shift, constraint 4.42 forces the time counter of the downtime to be greater than or equal to the number of time units in one day. When a task is completed in a shift, constraint 4.43 restricts the time counter to stop after the technicians are picked-up and transferred to the vessel. Constraints 4.44 does the same but for the first shift of the planning period, as this shift has no preceding shift.

$$l_{ms} \geq \sum_{v \in V_m} (t_{(m+|M^-|)vs} + T^{PD} x_{mvs} - t_{mvs}), \qquad m \in M^P, s \in S, \tag{4.45}$$

$$\sum_{v \in V_m} (t_{(m+|M^-|)vs} + T^{PD} x_{mvs} - t_{mvs}) \geq T^{MIN} x_{mvs}, \qquad m \in M^P, s \in S \tag{4.46}$$

For preventive tasks the turbines are only shut down during the maintenance tasks. Constraint 4.45 makes sure that the downtime is at least as much as the time between the start of the drop-off task till the moment that the technicians are transferred back to the vessel. Constraint 4.46 avoids that the technicians are left at the turbine for a time period that is so short that they in reality do not have time to perform any maintenance. This is avoided by means of a minimal time for preventive maintenance tasks.

Constraints for the balance of technicians:

$$p_{mvs} - P_n - p_{nvs} \leq (Q_v - P_n)(1 - z_{mnvs}), \quad m \in M\backslash\{|M|\}, n \in M\backslash\{0\}, v \in V_m \cap V_n, s \in S \tag{4.47}$$
$$p_{mvs} - P_n - p_{nvs} \geq (-P_n - Q_v)(1 - z_{mnvs}), \quad m \in M\backslash\{|M|\}, n \in M\backslash\{0\}, v \in V_m \cap V_n, s \in S \tag{4.48}$$

Constrained 4.47 and 4.48 are linearized constraints that ensure the balance of technicians for consecutive tasks m and n that are performed sequentially. The constraints state that the number of technicians at the vessel directly after task n must be equal to the sum of the number of technicians directly after task m and the number of technicians required for task n.

$$p_{mvs} \leq (Q_v - P_m)x_{mvs}, \quad m \in M^-, v \in V_m, s \in S \tag{4.49}$$
$$p_{mvs} \leq Q_v x_{mvs}, \quad m \in M^+, v \in V_m, s \in S \tag{4.50}$$
$$p_{mvs} \geq -P_m x_{mvs}, \quad m \in M^+, v \in V_m, s \in S \tag{4.51}$$
$$p_{mvs} \leq Q_v x_{mvs}, \quad m = \{0\} \cup m = \{|M|\}, v \in V_m, s \in S \tag{4.52}$$
$$p_{mvs} \geq (Q_v - P_m)x_{mvs}, \quad m \in M^-, v \in V_m, s \in S | E_m = 1 \tag{4.53}$$

Constraints 4.49 until 4.53 make sure that the vessel capacity is never exceeded.

The domains of the decision variable

$$x_{mvs} \in [0,1], \quad m \in M, v \in V_m, s \in S \tag{4.54}$$
$$y_{ijvs} \in [0,1], \quad i,j \in N, v \in V, s \in S, i \neq j \tag{4.55}$$
$$z_{mnvs} \in [0,1], \quad i \in N^W, m,n \in M_i, v \in V_m \cap V_n, s \in S \tag{4.56}$$
$$w_{ivs} \in [0,1], \quad i \in N, v \in V^A, s \in S \tag{4.57}$$
$$f_{mvs} \in [0,1], \quad m \in M, v \in V_m, s \in S \tag{4.58}$$
$$t_{mvs} \geq 0, \quad m \in M, v \in V, s \in S \tag{4.59}$$
$$l_{ms} \geq 0, \quad m \in M, s \in S \tag{4.60}$$
$$p_{mvs} \geq 0, integer, \quad m \in M, v \in V_m, s \in S \tag{4.61}$$
$$c_m \geq 0, integer, \quad m \in M \tag{4.62}$$

Constraints 4.54 until 4.62 determine the domains of the decision variables.

4.2. Model adjustments

In order to make the mathematical problem applicable for optimizing the maintenance support vessel route and schedule of an OWSF, multiple adjustments have been made. In chapter 2 the requirements for the optimization model of routing and scheduling maintenance support vessels of an OWSF are listed. Figure 4.2 shows the requirements and whether the model of Raknes et al. meets the requirements.

	Raknes et al. (2017) [32]
Maintenance tasks are allocated to different nodes	v
Multiple vessels with different routes	v
Different characteristics for vessels	v
Multiple services orders per tour	
Downtime cost related to the maintenance task	v
Downtime cost related to weather conditions	v
Distinction between preventive and corrective maintenance tasks	v

Figure 4.2: Model requirements and the compliance of the model of Raknes et al.

The model of Raknes et al. lacks the ability to perform multiple service orders per tour. This requirement is assessed as not included because the model can only perform multiple maintenance tasks allocated to the same node. This limitation is due to the fact that in the model of Raknes et al. the nodes represent wind farms. It would be unrealistic that a vessel performs maintenance tasks at different wind farms during the same shift. Therefore, the first adjustment required to make the model applicable for this research is that the nodes represent units (wind or solar) in stead of wind farms. In the model of Raknes et al. it is possible to allocate different maintenance tasks to different nodes. Therefore, the next required adjustment is to enable the vessels to visit multiple nodes during one shift. Furthermore, the model of Raknes et al. considers multiple types of vessels with different characteristics. A set of RHIBs is added to the input parameters and in order to include the third type of vessels some small adjustments of the mathematical formulation are required. Figure 4.3 shows a representation of the routing and scheduling model for an OWSF.

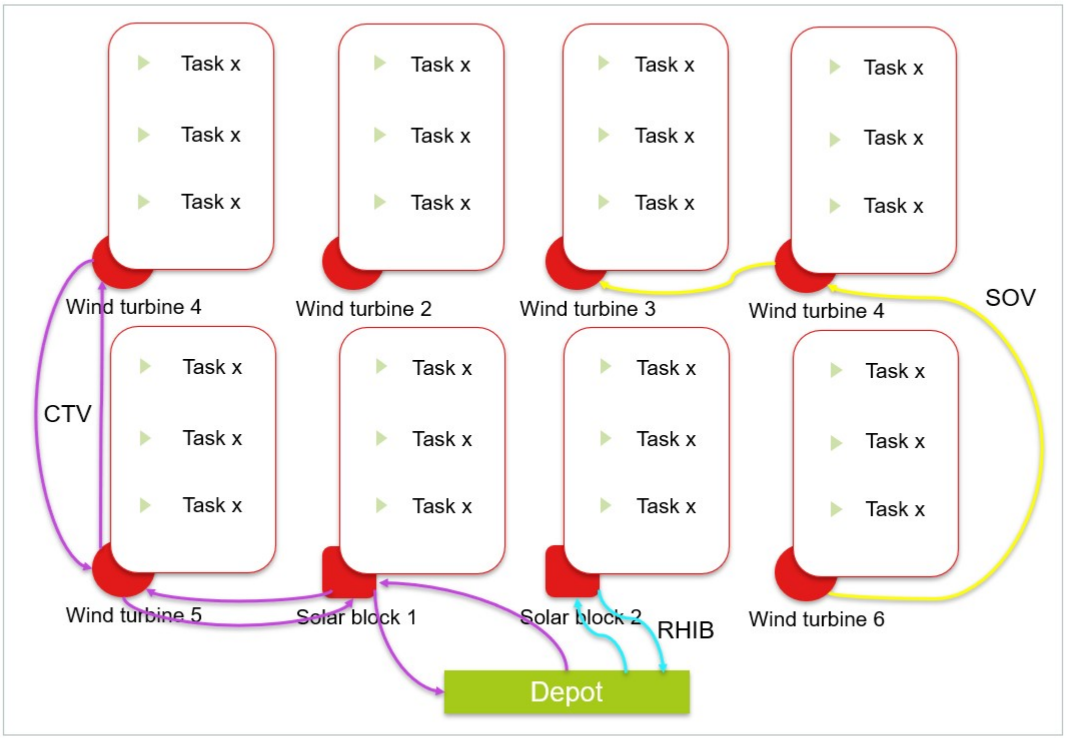


Figure 4.3: Representation of the routing and scheduling model for an OWSF

Subsection 4.2.1 first describes some improvements of detected errors in the model of Raknes et al.. Subsection 4.2.2 describes the adjustments applied to make the nodes represent the units and subsection 4.2.3 shows the adjustments required to enable the vessels to visit multiple nodes during a shift. Subsection 4.2.4 lists the implemented adjustments in order to include RHIBs as the third type of vessel.

4.2.1. Errors in the mathematical model of Raknes et al.

Firstly, some errors are found in the mathematical formulation of Raknes et al. The errors and the implemented adjustments are explained in this subsection.

In constraint 4.31, the right side of the formula is summed over j. However, as only the begin depot 0 is considered as j, the sum is redundant. The constraint is replaced by constraint 4.31a

$$t_{mvs} \geq \sum_{j \in N^W} T^T_{0iv} y_{0ivs} - T^{SHIFT}_s (1 - x_{mvs}), \qquad i \in N^W, m \in M^-_i, v \in V^A_m, s \in S, \tag{4.31}$$

$$t_{mvs} \geq T^T_{0iv} y_{0ivs} - T^{SHIFT}_s (1 - x_{mvs}), \qquad i \in N^W, m \in M^-_i, v \in V^A_m, s \in S, \tag{4.31a}$$

In constraint 4.46 the minimum time for performing a maintenance task is implemented as T^{MIN}. However, T^{MIN} represents the minimum time window for a vessel to leave the depot. T^{MINt} is introduced as the minimum time a maintenance task should be performed (see constraint 4.46a).

$$\sum_{v \in V_m} (t_{(m+|M^-|)vs} + T^{PD} x_{mvs} - t_{mvs}) \geq T^{MIN} x_{mvs}, \qquad m \in M^P, s \in S, \tag{4.46}$$

$$\sum_{v \in V_m} (t_{(m+|M^-|)vs} + T^{PD} x_{mvs} - t_{mvs}) \geq T^{MINt} x_{mvs}, \qquad m \in M^P, s \in S, \tag{4.46a}$$

4.2.2. The nodes represent units

Secondly, the model of Raknes et al. considers multiple wind farms each represented by a node. In the OWSF model the nodes represent the wind turbines and solar units. Which means that there are still multiple maintenance tasks per node, but there is no internal average travel time per node. Therefore, is the part of the objective function (equation 4.1b) that represents the internal travel costs excluded:

$$+ \sum_{m \in M^-} \sum_{v \in V_m} \sum_{s \in S} C^{IT}_v x_{mvs} \tag{4.1b}$$

Furthermore, adaptations are required in the constraints for time management. The constraint 4.34 that determines the minimal time between the start time of two consecutive tasks is replaced because there is no travel and transfer time between the start times of tasks at the same turbine of solar unit. It is replaced by constraint 4.34a.

$$t_{mvs} - t_{nvs} + T^{IT}_{iv} + T^{PD} \leq T^{SHIFT}_s (1 - z_{mnvs}), \qquad i \in N^W, m \in M \backslash \{|M|\}, n \in M^-_i \cup M^+_i, v \in V_m \cap V_n, s \in S | m \neq n \tag{4.34}$$

$$t_{mvs} - t_{nvs} + \delta \leq T^{SHIFT}_s (1 - z_{mnvs}), \qquad i \in N^W, m \in M^-_i \cup M^+_i, n \in M^-_i \cup M^+_i, v \in V_m \cap V_n, s \in S | m \neq n \tag{4.34a}$$

Hereby is the time between the start times of consecutive tasks not equal to greater than the average travel time and the transfer time, but equal to or greater than a small non-negative number. Which means that consecutive tasks on the same unit can be started just after each other.

If consecutive tasks are performed at different turbines or solar units the vessel must travel between the turbines. Therefore, constraint 4.41+ is added to the constraints of precedence.

$$z_{mnvs} \leq y_{jivs}, \qquad m \in M_j^- \cup M_j^+, n \in M_i^- \cup M_i^+, i,j \in N, v \in V_m \cap V_n, s \in S | i \neq j \tag{4.41+}$$

In the model of Raknes et al. constraint 4.41 makes sure that the subsequent task of a maintenance task that requires the vessel to stay at the turbine is the related pick-up task. In the OWSF model multiple tasks can be performed at the same unit. Therefore constraint 4.41 is replaced by constraint 4.41a which ensures that for tasks that require the vessel to stay, only subsequent tasks at other units can be started after this task is finished.

$$z_{mnvs} = x_{mvs}, \qquad m \in M^-, n = m + |M^-|, v \in V_m, s \in S | E_m = 1 \tag{4.41}$$

$$t_{nvs}x_{mvs} \geq t_{(m+|N|)vs}x_{nvs}, \qquad i,j \in N^W, m \in M_i, n \in M_j, v \in V_m \cap V_n, s \in S | i \neq j, E_m = 1 \tag{4.41a}$$

4.2.3. A vessel can visit multiple nodes during a shift

In the model of Raknes et al. a vessel can only visit one node per shift. In the OWSF model the vessel can visit multiple nodes during one shift. Therefore, the following adjustments are implemented.

For the flow of CTVs constraint 4.6 is excluded, as the CTV can travel more than twice:

$$\sum_{i \in N} \sum_{j \in N} y_{ijvs} \leq 2, \qquad v \in V^C, s \in S \tag{4.6}$$

For the flow of AVs as well the constraint 4.10 that limits the number of travels is removed:

$$\sum_{i \in N} \sum_{j \in N} y_{ijvs} \leq 1, \qquad v \in V^A, s \in S \tag{4.10}$$

In the constraints for time management the constraint 4.35+ is added. The time between the start times of consecutive tasks that should be performed at different turbines or solar units must be greater than or equal to the travel time between the turbines or solar units and the transfer time.

$$t_{mvs} - t_{nvs} + T^{PD} + T^T_{jiv}y_{jivs} \leq T^{SHIFT}_s(1 - z_{mnvs}), \qquad i \in N^W, j \in N^W, m \in M_j^- \cup M_j^+, n \in M_i^- \cup M_i^+, v \in V_m \cap V_n, s \in S | m \neq n \tag{4.35+}$$

4.2.4. Addition of RHIBs

As FPV is generally serviced with RHIBs, a set of a third type of vessel (V^R) is added. The same constraints apply for RHIBs as for CTVs. RHIBs can service only the FPV units and CTVs can service both the wind turbines and the FPV units. This difference is defined in the input as the input includes the indication which vessel can be used for which task.

The constraints that handle the flow of CTVs (equations 4.2 till 4.5) are adjusted to apply also for the set of RHIBs (V^R):

$$\sum_{j \in N} y_{0jvs} = 1, \qquad v \in V^C \cup V^R, s \in S \tag{4.2a}$$

$$\sum_{i \in N} y_{i|N|vs} = 1, \qquad v \in V^C \cup V^R, s \in S \tag{4.3a}$$

$$y_{0|N|vs} = 1, \qquad v \in V^C \cup V^R, s \in S | (U^W_{vs} - L^W_{vs}) < T^{MIN} \tag{4.4a}$$

$$\sum_{i \in N} y_{ijvs} = \sum_{i \in N} y_{jivs}, \qquad j \in N^W, v \in V^C \cup V^R, s \in S \tag{4.5a}$$

The constraints 4.36 and 4.37 make sure that each task has a previous and a following task except for the depot tasks. These constraints apply as well for the set of RHIBs. Therefore, constraints 4.36+ and 4.37+ are added.

$$x_{mvs} = \sum_{n \in M \setminus \{0\}} z_{mnvs} \qquad m \in M \setminus \{|M|\}, v \in V_m^R \cap V_n^R, s \in S \qquad (4.36+)$$

$$x_{mvs} = \sum_{n \in M \setminus \{|M|\}} z_{nmvs} \qquad m \in M \setminus \{|0|\}, v \in V_m^R \cap V_n^R, s \in S \qquad (4.37+)$$

Furthermore, other small adjustments are required to include the set of RHIBs in other constraints. Constraint 4.14, 4.28 and 4.29 are adapted in order to be applied to the set of RHIBs as well as for the set of CTVs. Constraint 4.14a ensures that the depot tasks are performed by each CTV and RHIB during each shift. Constraints 4.28a and 4.29a make sure the start time of drop-off tasks must be greater than or equal to both the lower bound of the weather window and the travel time to the wind farm.

$$x_{mvs} = 1, \qquad v \in V^C \cup V^R, m = 0 \cup |M|, s \in S \qquad (4.14a)$$

$$t_{mvs} \geq L_{vs}^W \sum_{j \in N} y_{jivs} - T_s^{SHIFT}(1 - x_{mvs}), \qquad i \in N^W, m \in M_i^-, v \in V_m^C \cup V_m^R, s \in S \qquad (4.28a)$$

$$t_{mvs} \geq \sum_{j \in N} T_{jiv}^T y_{jivs} - T_s^{SHIFT}(1 - x_{mvs}), \qquad i \in N^W, m \in M_i^-, v \in V_m^C \cup V_m^R, s \in S \qquad (4.29a)$$

With the above described adjustments of the mathematical model of Raknes et al. a new mathematical model is created. The new mathematical model meets the requirements described in chapter 2.

5
Model verification

This chapter describes the verification of the maintenance support vessel route and schedule optimization for an OWSF. Thereby it answers the sub-question *Is the optimization model for maintenance support vessel routing and scheduling for an OWSF correctly implemented?*. Section 5.1 explains the implementation of the model. Section 5.2 explains the baseline scenario input for the verification process and the related output. The model is verified with three scenarios. The input and related output are described in section 5.3.

5.1. Baseline scenario

The baseline scenario is a virtual scenario used for the verification of the model. The virtual OWSF contains three wind turbines and one FPV solar block. Figure 5.1 gives a representation of the OWSF. For the maintenance tasks six types of maintenance tasks are considered. As shown in figure 5.2 the installations are divided in parts, namely the nacelle (N), the electricity (E), and solar (S). For each part an inspection task is considered as preventive maintenance and a replacement task as corrective maintenance. The required maintenance tasks in the planning period per wind turbine and solar unit are listed in figure 5.1 at the allocated turbine or solar unit.

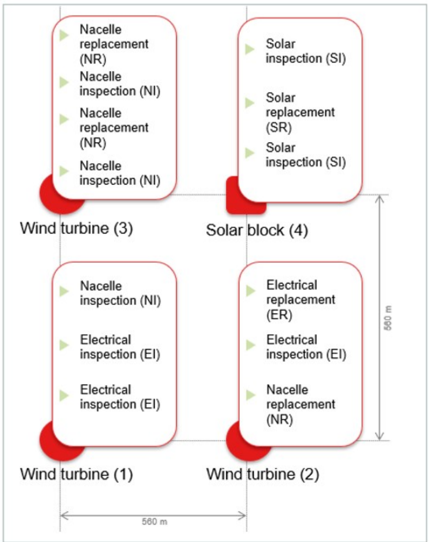


Figure 5.1: Representation of the baseline scenario

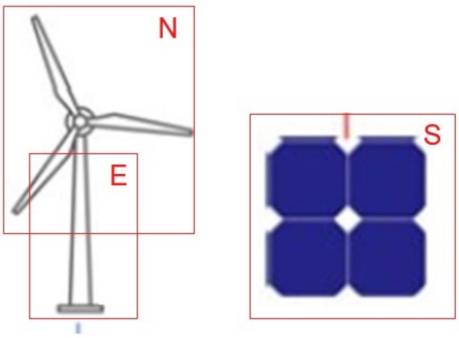


Figure 5.2: Division for the different task types

Further general information for the baseline scenario is listed below:

- Distance from the port to the wind farm: 20 km
- Vessels:
  - 3 CTVs:
    - capacity: 35 technicians,
    - average speed: 30 km/h,
    - cost: €100 fixed cost per shift + €200 per hour
    - minimal weather window for the vessel to leave the depot: 2 h
  - 1 SOV:
    - capacity: 40 technicians,
    - average speed: 28 km/h,
    - cost: €1000 fixed cost per shift + €500 per hour
    - cost for staying offshore: €200 per night,
    - maximum shifts the vessel can stay offshore: 28
  - 1 RHIB:
    - capacity: 6 technicians,
    - average speed: 56 km/h,
    - cost: €100 fixed cost per shift + €100 per hour
    - minimal weather window for the vessel to leave the depot: 2 h
- Time required to transfer technicians from the vessel onto the unit (transfer time): 0.5 h
- Minimum time a task should be executed: 0.25 h

Figure 5.3 presents the input parameters for the baseline scenario related to the task types. A task type can be preventive or corrective. The table lists which type of vessel is required for the type of task. The number of technicians that is required per type of task is included. Furthermore, the required duration of the task is indicated. For some tasks it is required that the vessel stays at the turbine or solar unit during the execution of the task. In the baseline scenario only nacelle replacement type of tasks require the vessel to stay. The penalty cost for not completing a task is higher in the baseline scenario for preventive maintenance than for corrective maintenance. This is required due to the difference in downtime cost. For corrective tasks the down time starts at the beginning of the planning period, and ends when the task is completed. With the models objective to reduce the downtime costs, this gives incentive to perform the corrective maintenance tasks. However, for preventive tasks the downtime is equal to the duration of the task because it is assumed that the unit is turned down during the execution of the task in the baseline scenario. Therefore, execution of a preventive task increases the downtime costs. The penalty cost for not completing a task must be high enough to push the model to include the execution of the preventive maintenance tasks in the solution. In addition, a penalty cost for the remaining hours of work is included in order to give incentive to completing tasks that are started already. In the baseline scenario it is assumed that the completion of corrective tasks is more important than the completion of preventive tasks.

	Electrical inspection (EI)	Electrical replacement (ER)	Nacelle inspection (NI)	Nacelle replacement (NR)	Solar inspection (SI)	Solar replacement (SR)
Preventive (P)/ Corrective (C)	P	C	P	C	P	C
Vessel	SOV, CTV	SOV, CTV	SOV, CTV	SOV	SOV, CTV, RHIB	SOV, CTV, RHIB
Number of technicians	2	3	3	5	2	2
Duration (h)	8	3	4	5	1	2
Vessel stay requirement	no	no	no	yes	no	yes
Penalty cost for not completing (€)	1 000 000	200 000	1 000 000	200 000	1 000 000	200 000
Penalty cost for remaining hours of work (€/h)	100	200	100	200	100	200

Figure 5.3: Input parameters for the type of tasks of the baseline scenario

Figure 5.4 shows the input parameters for the baseline scenario related to the shifts. The planning period of the baseline scenario exists of four shifts. Each shift has a duration of eight hours. For the weather windows are 0.00 is defined as the beginning of the shift. For each shift the spare part availability per task is taken into account. In the baseline scenario all spare parts are available each shift, so each task can be performed during each shift. The downtime cost is the same during each shift in the baseline scenario.

	Shift 1	Shift 2	Shift 3	Shift 4
Duration (h)	8	8	8	8
Weather window CTV	0.00 till 9.00	0.00 till 9.00	0.00 till 9.00	0.00 till 9.00
Weather window SOV	0.00 till 10.00	0.00 till 10.00	0.00 till 10.00	0.00 till 10.00
Weather window RHIB	1.00 till 9.00	1.00 till 9.00	1.00 till 9.00	1.00 till 9.00
Spare part availability	For all tasks complete	For all tasks complete	For all tasks complete	For all tasks complete
Perform extra preventive tasks according to energy production	Yes for all tasks	Yes for all tasks	Yes for all tasks	Yes for all tasks
Downtime cost (€/h)	Wind: 1000 Solar: 100	Wind: 1000 Solar: 100	Wind: 1000 Solar: 100	Wind: 1000 Solar: 100

Figure 5.4: Input for the shifts of the baseline scenario

5.2. Verification scenarios

In order to validate the model, three other virtual scenarios are constructed:

1. Different weather conditions per shift:
   Shift 1 and 2 have high wind speeds and low solar radiation. In the input that results in small weather windows, no extra preventive maintenance tasks can be performed at the wind turbines, the downtime cost for wind turbines is high, and the downtime cost for the solar units is low. Shift

3 and 4 are windless and have high solar radiation. This means that weather windows for shift 3 and 4 are equal to the shift duration, no extra preventive maintenance tasks can be performed at the solar units, the downtime cost for the wind turbines is low, and the downtime cost for the solar units is high.

2. The use of an RHIB is very expensive:
The cost of using an RHIB is at least 10 time higher than the use of the other vessels.

3. The cost of an SOV staying offshore is very high:
The cost of an SOV staying offshore between shifts is 10 times higher than in the baseline scenario.

The verification of the model is summarized in figure 5.5. If the check box it ticked it means that the output is in line with the expected outcome. The detailed results of the verification is presented in appendix B.

Scenario	Variation	Expected outcome	Check
1	Different weather conditions per shift	Solar tasks are executed during low solar radiation shifts and wind tasks are executed during low wind speed shifts	V
2	The use of an RHIB is very expensive	No RHIB used	V
3	The cost of an SOV staying offshore is very high	SOV does not stay offshore	V

Figure 5.5: Summary of the model verification

Figure 5.6 presents the cost results for the different scenarios. Scenario 1 results in an increase in travel cost. This is due to the division in when to execute the solar and wind turbine maintenance tasks. This results in more transits than in the baseline scenario. Furthermore, an increase in cost of the SOV staying offshore is a result of scenario 1. This is due to the high downtime cost of the wind turbines during the first two shifts. This causes the model to choose for executing wind turbine maintenance tasks in the last shifts, which results in the SOV staying offshore for a longer period than in the baseline scenario. The increase in downtime cost is due to the high downtime cost for wind turbines during the first two shifts. As the downtime starts at the beginning of the planning period for corrective maintenance tasks, and some of the corrective tasks can only be performed with the support of the SOV. The increase in penalty cost for scenario 1 is as well a results from executing tasks in the last shifts in order to reduce the downtime costs of preventive maintenance tasks. Scenario 2 only results in higher travel costs due to the use of a CTV in stead of an RHIB for the solar unit maintenance tasks, and the use of a CTV is more expensive than the use of an RHIB. Scenario 3 results in a decrease in travel cost because of excluding the use of an SOV. However, this causes an increase in downtime cost and penalty cost because one type of corrective maintenance task can only be performed with an SOV.

Cost type	Base scenario	Scenario 1	Scenario 2	Scenario 3
Travel cost	€ 4,869.79	€ 5,742.35	€ 44,614.58	€ 2,712.94
SOV stay cost	€ 800.00	€ 1,200.00	€ 800.00	€ 0.00
Downtime cost	€ 142,900.01	€ 153,529.66	€ 142,854.06	€ 341,940.58
Total cost	€ 148,569.80	€ 160,472.01	€ 188,268.64	€ 344,653.52
Penalty cost corrective tasks	€ 6,000,000.00	€ 12,000,000.00	€ 6,000,000.00	€ 24,000,000.00
Penalty cost preventive tasks	€ 30,000,000.00	€ 110,000,000.00	€ 30,000,000.00	€ 30,000,000.00
Penalty cost for not completing a task in the planning period	€ 0.00	€ 0.00	€ 0.00	€ 3,000.00
Total penalty cost	€ 36,000,000.00	€ 122,000,000.00	€ 36,000,000.00	€ 54,003,000.00
Total cost	€ 36,148,569.80	€ 122,160,472.01	€ 36,188,268.64	€ 54,347,653.52

Figure 5.6: Comparison of the outputted costs in the verification process

6 Case study

The model is applied to a case study. In this chapter the input, output and conclusions of the case study are presented. With the case study sub-question 5 and 6 are answered: *What is the optimal route and schedule of maintenance support vessels for an offshore wind and solar farm case study?* and *How can the optimal route and schedule for maintenance support vessels for the case study be validated?*. For validation of the model a TNO tool called The O&M Calculator is considered. However, this tool appeared not to be comparable. This is explained in section 6.1. Therefore, two scenarios are analysed. Section 6.2 describes the scenarios and input parameters. Section 6.3 presents the results of the model for the case study and 6.4 validates the results by means of an analysis of the influential factors.

6.1. TNO tool comparison

The O&M Calculator is part of ECN's Operations & Maintenance Cost Estimator (OMCE) concept. The OMCE concept enables wind farm operators to make use of their own field data and develop a cost effective O&M strategy. The O&M Calculator provides the expected O&M effort and associated costs for the coming period of 1-5 years. It is a time simulation program and uses the relevant operational information processed by the OMCE data analysis tools as input.

The O&M Calculator is a simulation tool. It performs the inputted number of simulations and gives the average of the simulations per variable. The tool includes default wind farm input. The input can be adjusted to make it applicable to the given wind farm. The main output of the O&M Calculator consists of the availability of the wind farm, the cost per kilowatt-hour per year, repair costs per year, revenue losses per year, and total effort per year. The results are broken down to a detailed level. The logistic results include the number of hours each vessel is used per year. This result is relevant for the research as the OWSF model only considers the cost of the vessel usage, the cost of an SOV staying offshore, and the downtime costs.

Comparison of the working of the O&M Calculator and the OWSF model showed that the tools are not compatible. The results can not be compared due to:

- The difference in analysis period
  The O&M Calculator simulates one year of the wind farm operation. Based on the mean time to failure of the components (MTTF) the required maintenance per day is generated. The OWSF model optimizes the route and schedule for a limited period (up to a week), due to the high computational time of the model. The MTTFs of all considered components are between 26 and 4000 weeks and are on average 1088 weeks. This means that for a realistic OWSF with 60 turbines and 20 solar units a certain maintenance task is on average required every 25 weeks. So, the required maintenance tasks in one year differ significantly per week. Therefore, an analysis of 1 week is not comparable to the results of the O&M Calculator for 1 year.

- The way the tools account for travel time of the vessels
  In the O&M Calculator an average travel time is inputted for each type of vessel calculated from the average distance from the port to the wind farm. In the OWSF model the travel time is specified for each possible path between the port, the turbines, and the solar units. This travel time is calculated from the exact distances.

- The types of maintenance tasks per failure of a component
  The O&M Calculator accounts for multiple types of maintenance tasks per failure of a component. A component's failure is divided in multiple repair classes with a percentage of the failure occurrence. So for instance, a failure of component 'A' belongs 80% of the time to repair class 1 and 20% of the time to repair class 2. Each repair class requires other maintenance specifications. In the OWSF only the most frequent required maintenance tasks are taken into account. Hence, per component the repair class with the highest percentage is taken into account. Which is mostly the maintenance task that requires the least time. These differences have a direct consequence for the travel cost and an indirect consequence for the downtime costs. Difference that directly influence the downtime costs are related to the weather windows, the availability of the turbines, and the consideration of the downtime of the solar units.

- Different calculation of weather windows
  The weather windows for the vessels for both tools can be based on the same weather data. However, in the OWSF model the weather window is based on the first hour and the last hour of the day that meets the required weather conditions. If during the work shift weather conditions get worse and then get better again it is ignored by the OWSF model. The O&M Calculator takes each hour of the shift into account to determine the weather windows for the vessels. This can result in smaller weather windows and higher downtime due to the decrease in accessibility.

- Calculation of downtime costs
  In the O&M Calculator the downtime is calculated as a percentage of the farm that is down due to failure or maintenance actions. In the development of the OWSF model it is assumed that only the wind turbine or the solar unit where the failure or maintenance is allocated is turned down. The percentages used in the O&M calculator are higher than the downtime of one turbine. Therefore, it results in higher downtime costs. In the comparison of the downtime cost it is important to note that the downtime of the solar units are not taken into account in the O&M Calculator. This would result in an increase in the downtime costs. However, this increase of costs is not significant enough to compensate for the gap between the downtime costs due to the other differences between the two tools.

Because the OWSF model results can not be compared to the results of an other available tool the results are compared for two scenarios. The results of the scenarios are analysed to determine whether they are reasonable.

6.2. Case description

At the moment no offshore wind and solar farm is in operation. Therefore, the case study is applied to a virtual wind and solar farm. In order to approach reality the virtual scenario is based on an operating wind farm, namely The Prinses Amaliawindpark in the Dutch North Sea. The wind farm is in operation since 2008. It is located 23 km from its maintenance port IJmuiden and contains 60 turbines. The virtual wind and solar farm has the same location and distance to its maintenance port as the Prinses Amaliawindpark. It consists of six wind turbines and two floating solar units. The location of the wind turbines and solar blocks is based on the average distance between the wind turbines in the Prinses Amaliawindpark (see figure 6.1).

Figure 6.1 shows the layout of the virtual wind and solar farm. The turbines and solar units are equally divided over the area of the Prinses Amaliawindpark. The defined nodes of the solar units represent the location where the technicians can access the solar unit from the vessel.

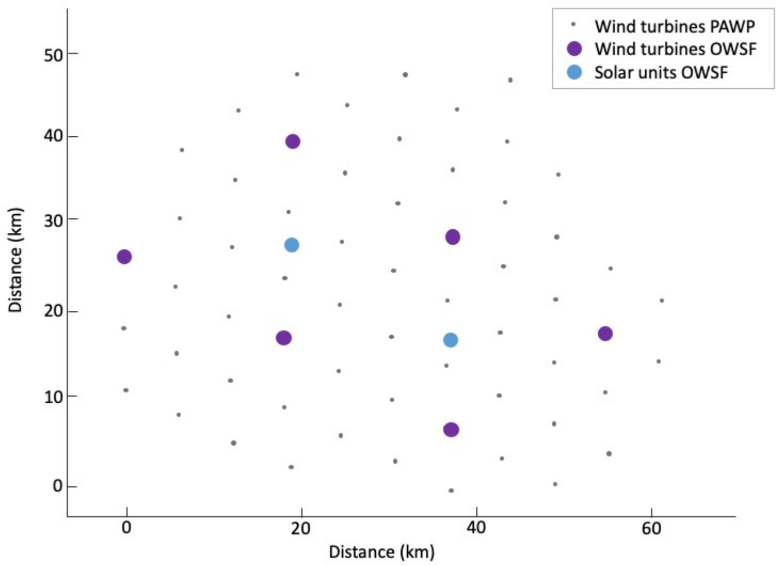


Figure 6.1: Layout of virtual wind and solar farm based on the layout of Prinses Amaliawindpark

The case study analysis the year 2014. The data and information about the required maintenance is provided by TNO based on their expertise in offshore wind farm maintenance. The data and information required for the solar units is extracted from an ongoing research at TNO in cooperation with Oceans of Energy. In the following subsections the data used in the case study is described.

6.2.1. Wind data

The O&M Calculator, an often used tool for O&M cost estimation at TNO, contains information about the required maintenance of a wind farm. Figure 6.2 shows the components of a wind turbine that require maintenance. According to the information from the O&M Calculator the type of maintenance, the required vessel, the duration, and the number of technicians required are appointed. Furthermore, it is determined whether it is required that the vessel stays at the solar units during the execution of the tasks and whether the turbine is turned off during the execution of the task. Maintenance required for the electricity infrastructure not located at the wind turbine is excluded. The input parameters of the maintenance tasks for the wind turbines is based on the most frequent required type of maintenance per component. The regular maintenance of a wind turbine is generally required twice per year and is commonly performed in months with low wind speeds.

Task type	P/C	Vessel	Duration (h)	Number of technicians	Vessel stay	Unit turned off during task execution
Wind Turbine regular maintenance	P	CTV / SOV	24	3	no	yes
Transformer 1	C	CTV / SOV	8	3	no	yes
Transformer 2	C	CTV / SOV	8	3	no	yes
Lightning protection/grounding	C	CTV / SOV	4	3	no	yes
Rotor System - blades	C	CTV / SOV	4	3	no	yes
Rotor system - hub	C	CTV / SOV	4	3	no	yes
Blade adjustment	C	CTV / SOV	4	3	no	yes
Drive train - main shaft/bearing	C	CTV / SOV	4	3	no	yes
Drive train - brake system	C	CTV / SOV	4	3	no	yes
Yaw gearbox	C	CTV / SOV	4	3	no	yes
Hydraulic system	C	CTV / SOV	4	3	no	yes
Control and protection system turbine	C	CTV / SOV	4	3	no	yes
Generator	C	CTV / SOV	4	3	no	yes
Control and protection system generator	C	CTV / SOV	4	3	no	yes
Generator lead/tranmission cables	C	CTV / SOV	4	3	no	yes
Transformer	C	CTV / SOV	4	3	no	yes
Machinery enclosure	C	CTV / SOV	4	3	no	yes
Turbine structure/tower	C	CTV / SOV	4	3	no	yes
Heating, ventilation, air conditioning	C	CTV / SOV	4	3	no	yes
Crane system	C	CTV / SOV	4	3	no	yes

Figure 6.2: Considered wind turbine maintenance tasks and related requirements

The Prinses Amaliawindpark contains 2 MW wind turbines with a hub height 80 meters. The ECN report written by Bulder, Bot and Bedon [90] provides the power curve date of the Pinses Amaliawind-park turbines (the dots in figure 6.3). With a Mean Square Error analysis the best fitted polynomial is found (see appendix) for the power curve data (the line in figure 6.3). The fitted 9th degree polynomial is used to determine the power loss during maintenance related to the weather conditions (see subsection 6.2.3).

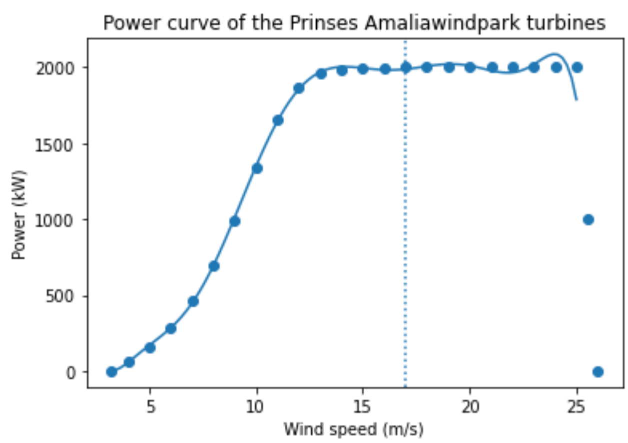


Figure 6.3: The power curve of the Prinses Amaliawindpark turbines

6.2.2. Solar data

The data and information for the maintenance of the solar units is extracted from an ongoing research at TNO. In the research about the feasibility of an OWSF, TNO is supported by Oceans of Energy who are specialized in offshore floating PV. TNO provided the components of the FPV units that require maintenance.

The integrated OWSF concept described by Houwing et al. [12] contains solar units of 6 MW. The units have an area of $0.17km^2(0.68x0.25km)$ including a vessel accessing platform.

Figure 6.4 presents the considered maintenance tasks for the solar units. According to the information from the ongoing research at TNO the type of maintenance, the required vessel, the duration, and the number of technicians required are appointed. Furthermore, it is determined whether it is required that the vessel stays at the solar units during execution of the tasks and whether the solar unit is turned off during the execution of the task. According to Oceans of Energy, inspection and cleaning is expected to be required twice a year for 7.5 hours with 4 technicians.

Houwing et al. [12] described that in the integrated concept the inverter and transformer are located at the wind turbine. In this research the maintenance tasks for the wind turbines are differently inputted than the maintenance tasks for the FPV units. This distinction makes it complicated to allocate the solar inverter and transformer maintenance tasks to the turbines coordinates. Therefore, it is assumed that the inverter and transformer of the FPV unit are located at the FPV unit itself. The maintenance of LVDC and MVDC is not considered in the case study as it is performed by cable laying vessels and the use of this type of vessel is not included in the OWSF model.

Component	Preventive (P)/ Corrective (C)	Vessel	Duration	Number of technicians	Vessel stay	Unit turned off during task execution
Mooring connenctions solar	C	CTV/RHIB	4	3	yes	no
Mooring system lines solar	C	CTV/RHIB	12	3	yes	no
Mooring system buoys solar	C	CTV/RHIB	8	3	yes	no
Mooring system chains solar	C	CTV/RHIB	12	3	yes	no
Mooring system anchors solar	C	CTV/RHIB	12	3	yes	no
Central inverter solar	P	CTV	4	3	no	no
Transformer solar	C	CTV	8	3	no	yes
j-tube solar	P	CTV	8	3	no	no
Inspection (and cleaning) solar	P	CTV/RHIB	7.5	4	no	no

Figure 6.4: Considered solar unit maintenance tasks and related requirements

6.2.3. Weather data

For the OWSF model multiple inputs are related to weather conditions:

- The weather windows for when each vessel type can operate: Each vessel type has a limitation in wind speed and wave height for when the vessel can operate safely. The lower bound of the weather windows is equal to the first hour of a day that the weather condition are below the given limits. The upper bound is equal to the last hour that the weather condition are below the given limits.
- The downtime cost per maintenance task per shift: In the case study is assumed that the maintenance cost is equal to the price of the power loss. Per shift the mean power generation per hour is determined according to the wind speed and the power curve.
- The limitation of doing extra maintenance tasks during a shift: In the model the constant k_{ms} determines the whether a preventive maintenance task can be performed as extra task during a shift. For instance, if the power output of the solar panels is very low during a shift it might be

favourable to perform an additional preventive task on the solar unit to make more effective use of the shift. When the solar panel has a very high power output, the number of preventive tasks should be limited as preventive tasks are not that time sensitive.

The power curve of the wind turbines is presented in figure 6.3. The data set of the Prinses Amaliawindpark of 2014 contains the wind speed and wave height per hour. Figure 6.5 presents the estimated average power output for each month of a 6 MW FPV unit located in the Dutch North Sea. Because, more accurate data is not publicly available the downtime cost of the solar units is determined according to figure 6.5.

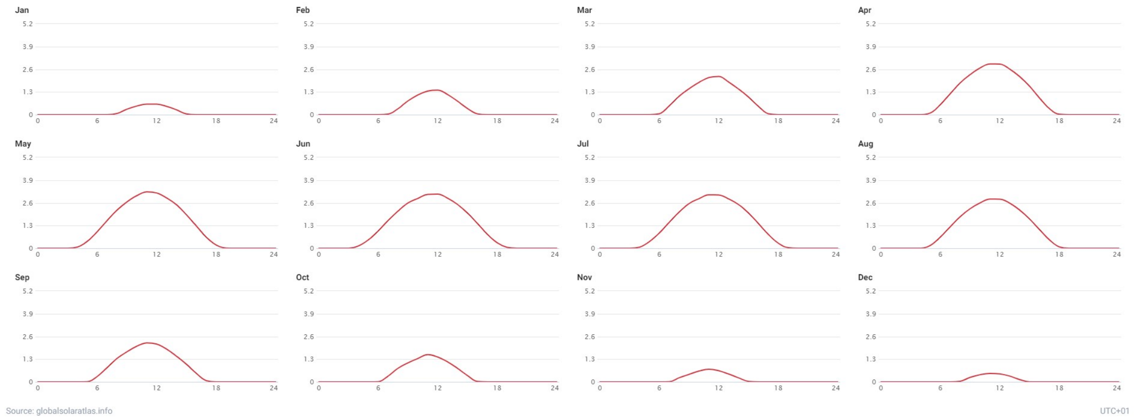


Figure 6.5: The estimated average power output of each month of a 6 MW FPV unit in the Dutch North Sea [91]

The average power output of a day per month, the assumption of whether the turbine of solar unit is shut down during the execution of the maintenance task, and the price of energy is used to determine the downtime costs. The default price of energy in the O&M Calculator tool of TNO is €0.07/kWh. Because this is tool is often used for O&M cost estimations for offshore wind farms it is assumed to be applicable for this research.

The determination of the k_{ms} constant is as well different, because of the difference in data availability. For wind turbine maintenance tasks the power limit for when not to perform extra preventive maintenance tasks is set to the maximum power output. For solar unit maintenance tasks it is based on the monthly estimated power output (see figure 6.6). In the months the estimated output is above the 500 kWh no extra preventive maintenance tasks can be performed.

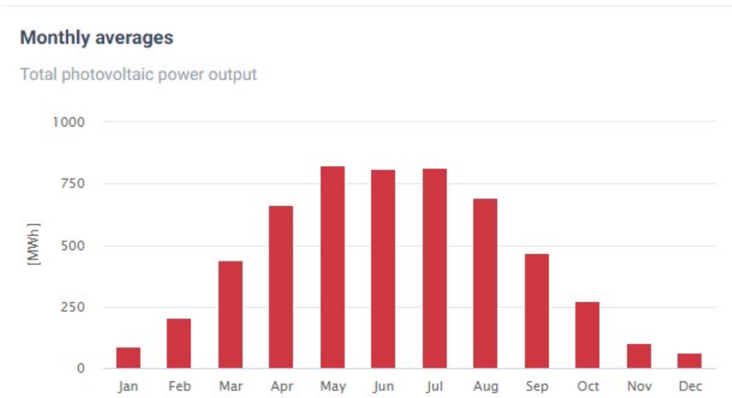


Figure 6.6: The estimated monthly average power output of a 6 MW FPV unit in the Dutch North Sea [91]

6.2.4. Vessel data

In the model are 3 types of vessels available. The average speed of the CTV, SOV and RHIB are based on the vessel specifications according to [92], [93], and [94] respectively. The other specifications of the vessels are extracted from the O&M Calculator tool of TNO. Figure 6.7 presents the vessel specifications.

Vessel type	Average speed (km/h)	Maximum number of technicians	Maximum wave height (m)	Maximum wind speed (m/s)	Cost	Cost per day	Cost for staying offshore per night	Cost per hour
CTV	37	12	1.5	12	€800000/year, €100/trip	€ 2,291.78	-	€ 286.47
SOV	18.5	36	3	15	€12000000/year	€ 32,876.71	€ 21,917.81	€ 1,369.86
RHIB	56	4	1	25	€1000/day	€ 1,000.00	-	€ 125.00

Figure 6.7: Vessel specifications

The cost extracted from the O&M Calculator in cost per year (C_{year}) and cost per trip (C_{trip}) is converted to cost per day (C_{day}) with equation 6.1. Which is converted to cost per hour (C_{hour}) with equation 6.2 for the CTV and RHIB. T^{shift} is the duration of the shift.

$$C_{day} = \frac{C_{year}}{365} + C_{trip} \tag{6.1}$$

$$C_{hour} = \frac{C_{day}}{T^{shift}} \tag{6.2}$$

For the SOV equation 6.3 is used to calculate the cost per night (C_{night}) and equation 6.4 to calculate the cost per hour.

$$C_{night} = \frac{C_{day}}{24}(24 - T^{shift}) \tag{6.3}$$

$$C_{hour} = \frac{C_{day}}{24} \tag{6.4}$$

The duration of all shifts is assumed to be 8 hours with one shift per day. Furthermore, the model includes a transfer time for technicians and spare parts to transfer from the vessel to the turbine or solar unit. The transfer time is assumed to be 15 minutes. In addition the model considers a minimum time of 30 minutes that technicians should stay at the turbine or solar unit. If this minimum time was not included, the solution can include the execution of a maintenance task for 5 minutes. Which is not realistic, because only accessing the right component to replace or inspect would take more time. Furthermore, a minimum time window is defined for a CTV or RHIB to leave the depot. When a weather window is too small it is not realistic for the vessel to leave the depot. This minimum time window is assumed to be 2 hours.

6.2.5. Penalty cost

The penalty costs are artificial costs that avoid postponing of the required maintenance tasks to a period beyond the planning horizon. Penalty costs are dependent on multiple factors, namely the potential downtime costs beyond the planning horizon which is related to the weather forecast, and the resource availability and costs in the period after the planning period [65]. Therefore, determining the penalty costs is a complex procedure. Dawid et al. [95] described a methodology that can be applied to calculate the penalty costs for not repairing a wind turbine.

In the OWSF model two types of penalty costs are applied. A penalty cost for a task that is not executed and a penalty cost per hour remaining of the required duration of a task that is not completed. Both type of penalty costs are defined for preventive and corrective tasks. For the purpose of this case study the costs are determined on the basis of the maximum travel costs to ensure that the travel costs do not constrain the execution of a maintenance task. The penalty costs are shown in figure 6.8.

Type of penalty cost	Corrective task	Preventive task
Per not executed task	€ 100.00	€ 100.00
Per hour left of the required duration of a not completed task	€ 300.00	€ 300.00

Figure 6.8: Penalty costs for case study

6.2.6. Scenarios

In the case study the optimal maintenance vessel route and schedule for an OWSF is investigated. The optimal route and schedule is dependent on weather conditions due to maintenance weather windows and related downtime costs. Therefore, from the overall input for the case study that is explained in the previous subsections two scenarios with different weather conditions are analysed. The case study scenarios cover 2 different months and consists of the first 4 shifts of the month. There is chosen for 4 shifts due to computational power limit of the OWSF model. The scenarios include 3 CTVs, 1 SOV, and 1 RHIB.

The two scenarios take place in different times of the year; in May and in February. May is a month with low wind speeds. Therefore, regular preventive maintenance of offshore wind turbines is often performed in May. February is a month with high wind speeds. The weather conditions result in limited weather windows for maintenance. Therefore, it is assumed that only corrective maintenance is performed in February. Accordingly, the required maintenance is determined for the two scenarios based on the given maintenance tasks in figures 6.2 and 6.4. Figure 6.9 shows an overview of the maintenance tasks chosen for the two scenarios. This means that these maintenance tasks must be performed in the 4 shifts of the scenario. Otherwise penalty costs will be applied.

Scenario	Task	Turbine (T) or Solar unit (S) number
May	Wind Turbine Regular Maintenance	T1
	Wind Turbine Regular Maintenance	T2
	Wind Turbine Regular Maintenance	T3
	Mooring system chains solar	S8
February	Transformer 1	T2
	Blade adjustment	T4
	Control and protection system turbine	T5
	Mooring system lines solar	S7

Figure 6.9: Overview of tasks for the case study scenarios

Figure 6.11 and 6.10 shows the weather windows for each vessel type for the shifts in May and February respectively. The weather windows are results of the weather data as described in subsection 6.2.3. For each month the first four shifts are taken. Each shift starts at 8.00 and ends at 16.00 where 0 means beginning of the shift and 8 end of the shift.

February	Shift			
	1	2	3	4
Shift duration	8	8	8	8
Lower bound CTV	0	0	0	0
Upper bound CTV	0	0	8	8
Lower bound SOV	0	0	0	0
Upper bound SOV	8	8	8	8
Lower bound RHIB	0	0	0	0
Upper bound RHIB	0	0	8	8

Figure 6.10: Weather windows for the February scenario

May	Shift			
	1	2	3	4
Shift duration	8	8	8	8
Lower bound CTV	0	0	0	0
Upper bound CTV	8	0	8	8
Lower bound SOV	0	0	0	0
Upper bound SOV	8	8	8	8
Lower bound RHIB	0	0	0	0
Upper bound RHIB	8	0	8	8

Figure 6.11: Weather windows for the May scenario

6.3. Results of the case study

The results of the OWSF model for the case study are shown in figure 6.12 and 6.13. The figures present the optimal route and schedule of maintenance support vessels for an OWSF for the different scenarios of the case study according to the OWSF model. The schedules include drop-off and pick-up tasks. For each maintenance task technicians are first dropped at the turbine or solar unit and later picked-up from the turbine or solar unit. The tasks indicated with a '+' represent the pick-up of the technicians of that maintenance task and the tasks without a '+' represent the drop-off of the technicians. In each maintenance task name the number after the '-' indicates at which turbine or solar unit the maintenance task is allocated, where numbers 1 till 6 indicate turbines and numbers 7 and 8 indicate floating solar units.

The February scenario (see figure 6.12) contains only corrective maintenance tasks. No maintenance is performed during the first and second shift. This is a result of the weather windows (see figure 6.10. The figure shows that 'CTV 2' is used for the maintenance of the wind turbines during shift 3 and 4. The CTV first drops off technicians at turbine 2, than at turbine 4 and then at turbine 5. The time between the drop-off tasks is equal to the travel time between the turbines and the time to transfer technicians from the vessel to the turbine. After approximately 4 hours the CTV picks up the technicians at turbine 4, then at turbine 5, and then at turbine 2. The sequence is related of drop-offs and pick-ups are related to the required duration of the tasks. During shift 4 the CTV drops off the technicians at turbine 2 and picks up the technicians after approximately 1.5 hours and returns back to the port. All vessels are always back at the port at 8.00 (end of shift) because the OWSF model does not include an inventive to return to the port earlier. The vessel costs are defined per kilometer. The RHIB is used for the maintenance of the floating solar unit during shift 3 and 4. The separate transport for the solar unit maintenance can be a result of the duration of the tasks, the vessel costs and speeds, and the penalty costs. This will be further analysed in section 6.4.

	Task	Start time (h)	Technicians at vessel after task	Task	Start time (h)	Technicians at vessel after task
	Shift 1			Shift 2		
CTV 1	Start at depot	0.00	0	Start at depot	0.00	0
	End at depot	8.00	0	End at depot	8.00	0
CTV 2	Start at depot	0.00	0	Start at depot	0.00	0
	End at depot	8.00	0	End at depot	8.00	0
CTV 3	Start at depot	0.00	0	Start at depot	0.00	0
	End at depot	8.00	0	End at depot	8.00	0
SOV 4	Start at depot	0.00	0	Start at depot	0.00	0
	End at depot	8.00	0	End at depot	8.00	0
RHIB 5	Start at depot	0.00	0	Start at depot	0.00	0
	End at depot	8.00	0	End at depot	8.00	0
	Shift 3			Shift 4		
CTV 1	Start at depot	0.00	12	Start at depot	0.00	0
	End at depot	8.00	12	End at depot	8.00	0
CTV 2	Start at depot	0.00	9	Start at depot	0.00	3
	Transformer 1-2	0.67	6	Transformer 1-2	0.67	0
	Blade adjustment-4	0.98	3	Transformer 1-2+	2.09	3
	Control and protection system turbine-5	1.29	0	End at depot	8.00	3
	Blade adjustment-4+	5.23	3			
	Control and protection system turbine-5+	5.54	6			
	Transformer 1-2+	7.75	9			
	End at depot	8.00	9			
CTV 3	Start at depot	0.00	0	Start at depot	0.00	0
	End at depot	8.00	0	End at depot	8.00	0
SOV 4	Start at depot	0.00	0	Start at depot	0.00	0
	End at depot	8.00	0	End at depot	8.00	0
RHIB 5	Start at depot	0.00	4	Start at depot	0.00	4
	Mooring system lines solar-7	0.45	1	Mooring system lines solar-7	0.45	1
	Mooring system lines solar-7+	6.11	4	Mooring system lines solar-7+	7.30	4
	End at depot	8.00	4	End at depot	8.00	4

Figure 6.12: The optimal route and schedule for the February scenario according to the OWSF model

The May scenario (see figure 6.13) contains scheduled preventive maintenance for the wind turbines and a corrective task for the solar unit. The results show that no maintenance is performed during shift 2 due to weather conditions (see figure 6.11). Furthermore, all required maintenance at different wind turbines is performed by one CTV during each shift. The Wind turbine Regular Maintenance takes 24 hours. Therefore it is performed during each shift with an available weather window. Remarkable is that these wind turbine maintenance tasks are performed by one vessel during a shift and not by separate vessels. During 3 shifts of 8 hours a 24 hour task can not be completed taking into account the travel time. This means that a penalty cost for not completing the tasks is applied anyway. The trade-off between one or separate vessels for the wind turbine maintenance is between the penalty cost per remaining hour of the task not completed and the travel costs of a CTV from the port to the OWSF and back. The dependency of the result on penalty costs and vessel costs is analysed in section 6.4. The solar unit maintenance is performed by the RHIB during shift 1 and 3. Similarly to the results of the May scenario, the transport for the solar unit maintenance is not combined with the transport for the wind turbine maintenance. The factors that influence the optimality of this result are further analysed in section 6.4.

	Task	Start time (h)	Technicians at vessel after task	Task	Start time (h)	Technicians at vessel after task
	Shift 1			Shift 2		
CTV 1	Start at depot	0.00	9	Start at depot	0.00	0
	Wind Turbine Regular Maintenance-2	0.67	6	End at depot	0.00	0
	Wind Turbine Regular Maintenance-3	0.97	3			
	Wind Turbine Regular Maintenance-1	1.25	0			
	Wind Turbine Regular Maintenance-1+	7.25	3			
	Wind Turbine Regular Maintenance-3+	7.50	6			
	Wind Turbine Regular Maintenance-2+	7.75	9			
	End at depot	8.00	9			
CTV 2	Start at depot	0.00	0	Start at depot	0.00	0
	End at depot	0.00	0	End at depot	0.00	0
CTV 3	Start at depot	0.00	0	Start at depot	0.00	0
	End at depot	0.00	0	End at depot	0.00	0
SOV 4	Start at depot	0.00	0	Start at depot	0.00	0
	End at depot	0.00	0	End at depot	0.00	0
RHIB 5	Start at depot	0.00	4	Start at depot	0.00	0
	Mooring system chains solar-8	0.43	1	End at depot	0.00	0
	Mooring system chains solar-8+	7.32	4			
	End at depot	8.00	4			
	Shift 3			Shift 4		
CTV 1	Start at depot	0.00	9	Start at depot	0.00	0
	Wind Turbine Regular Maintenance-2	0.67	6	End at depot	0.00	0
	Wind Turbine Regular Maintenance-3	0.97	3			
	Wind Turbine Regular Maintenance-1	1.25	0			
	Wind Turbine Regular Maintenance-2+	7.25	3			
	Wind Turbine Regular Maintenance-1+	7.50	6			
	Wind Turbine Regular Maintenance-3+	7.75	9			
	End at depot	8.00	9			
CTV 2	Start at depot	0.00	0	Start at depot	0.00	12
	End at depot	0.00	0	Wind Turbine Regular Maintenance-2	0.67	9
				Wind Turbine Regular Maintenance-3	0.97	6
				Wind Turbine Regular Maintenance-1	1.25	3
				Wind Turbine Regular Maintenance-1+	7.25	6
				Wind Turbine Regular Maintenance-3+	7.50	9
				Wind Turbine Regular Maintenance-2+	7.75	12
				End at depot	8.00	12
CTV 3	Start at depot	0.00	0	Start at depot	0.00	0
	End at depot	0.00	0	End at depot	0.00	0
SOV 4	Start at depot	0.00	0	Start at depot	0.00	0
	End at depot	0.00	0	End at depot	0.00	0
RHIB 5	Start at depot	0.00	4	Start at depot	0.00	4
	Mooring system chains solar-8	0.43	1	End at depot	0.00	4
	Mooring system chains solar-8+	7.32	4			
	End at depot	8.00	4			

Figure 6.13: The optimal route and schedule for the May scenario according to the OWSF model

In figure 6.14 the costs are presented of the two routes and schedules. The total costs in February is higher than the total costs in May. This is a result of the significant difference in downtime costs. In February the required maintenance tasks are corrective, this means the maintenance is scheduled after failure is occurred. For corrective maintenance tasks the downtime starts at the beginning of the planning period until the task is completed. Furthermore, due to the high wind speeds in February the downtime cost per hour for the wind turbines is higher than in May. Thus, the larger number of corrective maintenance tasks for wind turbines in combination with the high wind speed in February explains the difference in costs between May and February. The difference in travel costs is reasonable because in the May scenarios a CTV sails out during 3 shifts in stead of 2 shifts in the February scenario.

	February		May	
Travel cost	€	1,018.63	€	1,488.93
Downtime cost	€	19,125.65	€	1,863.85
Total cost	€	20,144.28	€	3,352.78

Figure 6.14: The costs results for related to routes and schedules for the February and May scenario

6.4. Result analysis

In the case study the optimal maintenance vessel route and schedule for an OWSF for two scenarios is presented. However, the results of the OWSF model for the case study scenarios are dependent of multiple factors. This section validates the results by investigating these dependencies.

6.4.1. Weather dependency

In the optimal route and schedule of maintenance support vessels for the February scenario no maintenance is performed in shift 1 and 2. This is due to weather conditions in combination with safety regulations that result in no possible time window during shift 1 and 2 to set sail with a CTV or RHIB (see figure 6.10). Likewise, no maintenance is performed during shift 2 for the May scenario (see figure 6.11). When the time windows of all shifts for both scenarios are set to 0 till 8, maintenance is as well performed during these shifts (see appendix D). If all vessels can sail during all shifts of the analysed period, corrective maintenance tasks are performed as early as possible in the planning period due to the increase of the downtime costs over time.

The three vessel types differ in maximum wave height and maximum wind speed. However, the difference in weather constraints for the CTV and RHIB do not result in difference in weather windows for the analysed scenarios. An analysis of the weather data of 2014 at the North Sea showed that 70% of the time both a CTV and an RHIB can support maintenance offshore according to safety regulations. Only 3% of the time a CTV can sail while an RHIB can not and 4% of the time an RHIB can sail while a CTV can not. So the results that during the shifts of the case study a CTV and RHIB have the same time windows gives a good representation of the overall correlation between the time windows of the two types of vessels.

Figure 6.11 and 6.10 show that the SOV can sail during all shifts for both scenarios. That the SOV is not used in the optimal route and schedule is expected to be a results of cost difference between the vessel types. This will be discussed in the following section.

6.4.2. Vessel cost and speed dependency

In addition to the difference in weather constraints, the vessel types differ in average speed, maximum number of technicians, and cost per hour (see figure 6.15). The optimal route and schedule for both case study scenarios do not include the use of an SOV. The cost of an SOV per hour in the case study is almost 5 times the cost per hour of a CTV. Additionally, the cost of an SOV staying offshore between shifts is almost 10 times higher than the cost of using a CTV for a full shift. In the case study the advantage of an SOV is that it can stay offshore for multiple shifts and can transport more technicians. So for the OWSF model to choose an SOV over a CTV, the costs of multiple trips to transport the required technicians from port to the OWSF by a CTV must be at least higher than the cost of an SOV staying offshore. For the size and the distance to shore of the OWSF in the case study it is unrealistic to use an SOV for the maintenance support [15].

In the results of both scenarios of the case study the solar unit maintenance is supported by the RHIB. In the case study the RHIB can only support the solar unit maintenance and not the wind turbine maintenance but a CTV can support the solar unit maintenance as well in the case study. The choice for an RHIB to support the solar unit maintenance can be a result of the cost difference or the speed difference between the two vessel types. To understand why an RHIB is scheduled for the solar unit maintenance in stead of a CTV the depency of the results on are the vessel type cost and speed are analysed.

	Average speed (km/h)	Maximum number of technicians	Cost per hour
CTV	37	12	€ 286.47
SOV	18.5	36	€ 1,369.86
RHIB	56	4	€ 125.00

Figure 6.15: Vessel specifications

For this analysis the February scenario is taken as base, because it includes various short maintenance tasks which gives more combinations of maintenance tasks that can be supported by the same vessel than for the May scenario. To analyse the cost dependency multiple simulations are performed with only varying the cost of the use of an RHIB. In the same way the speed dependency is analysed but than only varying the speed of an RHIB. Figure 6.16 shows the tipping point for when an RHIB is included in the optimal route and schedule for the case study related to the cost of an RHIB. Figure 6.17 shows the tipping point related to the speed on the RHIB. The tipping points can be explained by the following mathematical relation. Where C_{RHIB} and C_{CTV} are the cost in euro per hour of an RHIB and CTV respectively and v_{RHIB} and v_{CTV} are the speed in kilometer per hour of an RHIB and CTV respectively. This means that for this scenario the inclusion of an RHIB is only dependent of the cost and speed difference between the vessel types.

$$C_{RHIB} = \frac{C_{CTV}}{v_{CTV}} v_{RHIB} \tag{6.5}$$

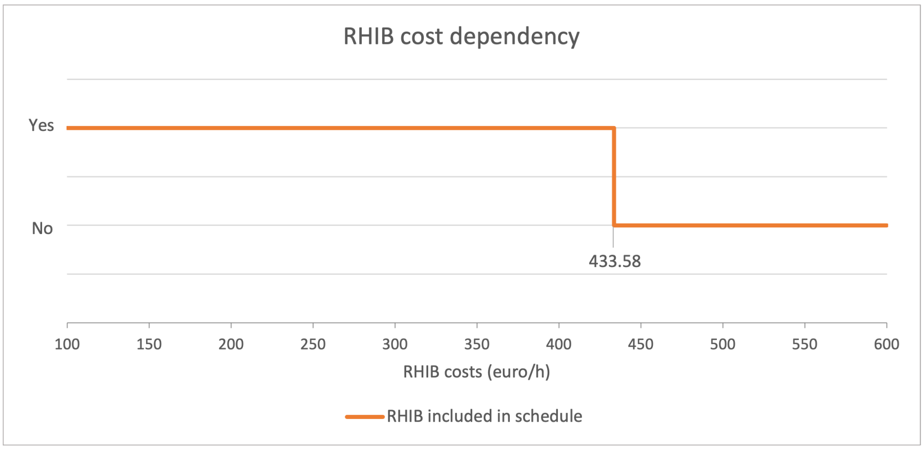


Figure 6.16: The effect of the cost of an RHIB on the inclusion of an RHIB in the schedule

In the results where the RHIB is not included in the optimal route and schedule, the solar unit maintenance is as well performed separately from the wind turbine maintenance (see appendix D). It is now supported by a CTV but it is not integrated with the support for the wind turbine maintenance. This can be a result of the number of required maintenance tasks in combination with the duration of the tasks. When the conditions of the scenario are changed it is still plausible that performing solar unit and wind turbine maintenance in one trip reduces costs compared to in separate trips.

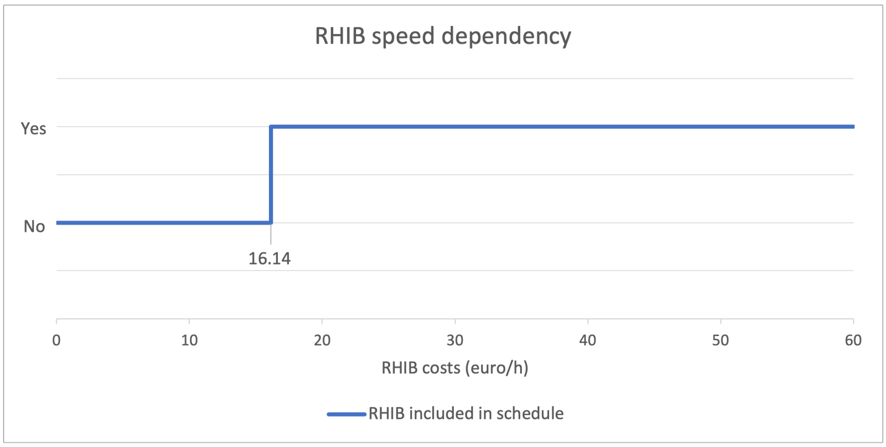


Figure 6.17: The effect of the speed of an RHIB on the inclusion of an RHIB in the schedule

6.4.3. Maintenance task duration dependency

To understand the relation between the required maintenance tasks and the choice to combine or split the transport four variants of the February scenario are simulated (see figure 6.18). To simplify the scenario, the number of tasks is reduced to two; one solar unit maintenance task and one wind turbines maintenance task. In variant 1 the vessel and task specifications are kept the same as the case study input. For the tasks this means that the wind turbine task has a duration of 4 hours and the solar unit task has a duration of 12 hours. In the results of this scenario the maintenance is performed separately. The OWSF model charges a penalty cost for the remaining hours of a maintenance task at the end of a shift. This explains that executing a task for as long as possible can minimize cost compared to combining the transport for the tasks. The penalty cost dependency will be further analysed in the following section. To avoid the effect of the penalty cost for remaining task duration, in variant 2 the duration of both tasks is reduced to 2 hours. The results of variant 2 as well contain task execution by separate vessels. A possible cause for this result is the low costs for an RHIB compared to a CTV. To confirm this cause the task duration is kept to 2 hours and the speed cost ratio is set equal to that of a CTV in variant 3. The optimal route and schedule for variant 3 does include combined transport for both maintenance tasks. However, when the vessel speed cost ratio is kept equal between a CTV and RHIB and the task duration is set to the initial values in variation 4 the tasks are performed separately again. Figure 6.18 summarized this analysis.

Variant	Description	Result
1	Two maintenance tasks with initial task duration and vessel initial cost and speed	Separate transport
2	Two maintenance tasks with reduced task duration and initial vessel cost and speed	Separate transport
3	Two maintenance tasks with reduced task duration and equal vessel cost speed ratio	Combined transport
4	Two maintenance tasks with initial task duration and equal vessel cost speed ratio	Separate transport

Figure 6.18: Summary of analysis to understand choice to combine or split the transport for maintenance tasks

Above described analyses of four variants of the February scenario indicates that the cost optimality of combining the transport for solar unit and wind turbine maintenance depends on speed cost ratios of the vessels and the duration of the maintenance tasks. The influence of the duration of the maintenance task on the optimal route and schedule is determined by the assigned penalty costs. The following section analyses the dependency of the optimal route and schedule on the assigned penalty costs.

6.4.4. Penalty cost dependency

Two types of penalty costs are included in the OWSF model to ensure that the required maintenance tasks are performed during the planning period. There is a penalty cost per maintenance task that is not executed in the planning period and a penalty cost for the remaining required hours to complete a maintenance task per shift. Both types of penalty costs are determined for corrective tasks and preventive tasks. The value of the penalty costs in the case study are presented in figure 6.19.

Type of penalty cost	Corrective task	Preventive task
Per not executed task	€ 100.00	€ 100.00
Per hour left of the required duration of a not completed task	€ 300.00	€ 300.00

Figure 6.19: Penalty costs for case study

The penalty cost for not completing a task only effects the execution of a task. Whereas the penalty cost for remaining hours of a maintenance tasks influences the schedule and routing. This penalty costs gives incentive to complete a task as soon as possible. It therefore forces the model to perform a task for as long as possible during a shift. This demotivates to perform multiple tasks at different turbines or solar units because the transportation time between the turbines or units is deducted from the task execution time. The dependency of the penalty cost per time unit on the optimal route and schedule is analysed for the February scenario of the case study.

The penalty cost dependency analysis is performed by varying the penalty costs, cost speed ratio of the RHIB and CTVs, and the number of maintenance tasks (see figure 6.20). In the first four iterations the penalty cost per time unit is reduced. Reducing the penalty cost per time unit with initial conditions of the February scenario does not result in combined transport for the wind turbine and solar unit maintenance tasks. A cause for that may be the low costs of an RHIB. Therefore, for the following iterations the speed cost ratio of a CTV and RHIB are set to equal. The reduction in penalty costs results in non-execution of the solar unit maintenance task. In iteration 5 till 7 the penalty cost for not completing a task is increased to ensure the execution of the tasks. With a penalty cost per task of 1000 euro the solar maintenance tasks are executed but still separate from the wind turbine maintenance tasks. To check whether the penalty cost dependency can be recognized when the number of maintenance tasks are reduced, iteration 8 and 9 are performed.

Iteration	Penalty cost per time unit of remaining duration of task (euro)	Penalty cost per full task not completed (euro)	Cost speed ratio RHIB and CTV	Maintanance tasks	Combined transport?
1	300	100	Initial values	Initial	No
2	200	100	Initial values	Initial	No
3	100	100	Initial values	Initial	No
4	0	100	Initial values	Initial	Solar maintenance not executed
5	0	300	Equal	Initial	Solar maintenance not executed
6	0	600	Equal	Initial	Solar maintenance not executed
7	0	1000	Equal	Initial	No
8	0	1000	Equal	3 wind turbine tasks, 1 solar unit task	No
9	0	1000	Equal	1 wind turbine tasks, 1 solar unit task	No

Figure 6.20: Summary of penalty cost analysis

The simple analysis to investigate the dependency of the optimal route and schedule on the value of the penalty costs indicates that there is no direct causal relation between the penalty cost per time unit and the combination of transport for wind turbine and solar unit maintenance. The relation is complex and includes more parameters. Downtime cost is a parameter that is expected to effect in combination with the penalty costs the optimal route and schedule. Downtime cost is charged per hour that a task is not completed yet for corrective tasks and for preventive tasks it is charged for hours a task is executed. It overlaps with when the penalty costs are charged.

This analysis indicates that the optimal route and schedule of maintenance support vessels for an OWSF are case dependent. However, whether it is cost optimal to use an RHIB or CTV for the maintenance of solar units is closely related to the cost speed ratio of the vessel types. If there is not too much deviation from the initial input for the case study the optimal route and schedule does not variate.

7

Conclusion and discussion

This chapter concludes the research, discusses the limitations of the work, and provides recommendations for further research.

7.1. Conclusion

In this research the OWSF model is developed to calculate the optimal routes and schedules of maintenance support vessels of an offshore wind and solar farm. It is developed from an earlier proposed route and schedule optimization model of Raknes et al.[6] for the maintenance support vessels of an offshore wind farm. The model of Raknes et al. is according to the conducted literature study the most applicable model for the optimization of the routes and schedules of the maintenance support vessels of an offshore wind and solar farm. Adjustments have been made to the optimization model of Raknes et al. in order to develop the OWSF model which is applicable to the route and schedule optimization of maintenance support vessels of an offshore wind and solar farm. The OWSF model is developed for this research to provide operational information about the effective use of vessels in the integrated maintenance support of wind turbines and solar units. The OWSF model is applied to a case study to calculate the optimal route and schedule of maintenance support vessels of an virtual OWSF. The virtual OWSF is based on the Prinses Amailia windpark in the Dutch North Sea. To validate the results the sensitivity of the optimal route and schedule is investigated.

This research aims to develop an optimal route and schedule of the maintenance support vessels for an OWSF. The main research question is *What is the optimal route and schedule of maintenance support vessels for an offshore integrated wind and solar farm?* The results of the case study show that the optimal route and schedule of maintenance support vessels of an OWSF includes separate trips to the turbines and solar units. This result indicates that integrating the maintenance support for offshore wind turbines and offshore floating solar does not decrease the travel and downtime costs. This contradicts the expectation that combining the maintenance support would increase the effective use of the time windows and the vessel transfers. The choice of using an RHIB for the solar unit maintenance and therefor not integrating the transport with the wind turbine maintenance transport is mainly because of the use of an RHIB is much cheaper than the use of a CTV or SOV. The low costs of using an RHIB for the solar unit maintenance appears to out way the potential cost reduction of sharing the transport.

7.2. Discussion

In this research a model is developed to calculate the optimal route and schedule of maintenance support vessels of an OWSF. However, multiple assumptions are applied in the development of the OWSF model and the model has several limitations.

The OWSF model analysis a planning period of a chosen length. When running the model the required maintenance tasks during the planning period are considered as static. This means that all the required maintenance tasks are known when the model starts running. Depending on the length of the planning period this might be unrealistic. Failure can occur unexpectedly. Which might change the optimality of the predetermined vessel route and schedule, as it results in downtime costs. For further research it is recommended to apply an algorithm that can simulate the dynamic need for corrective maintenance.

The model accounts for the travel cost as a cost for the travel between two nodes and is specified per vessel. Costs for a vessel to stay at the turbine during the execution of the maintenance is not included. Furthermore, currently in the maintenance of offshore wind farms the vessels are not paid for per hour or distance aside from the fuel costs. Vessels are leased or owned by the company executing or supporting the maintenance of the wind turbines [63]. However, the objective of the OWSF model in this research is increasing the effective use of the vessel trips. Minimizing the cost that is defined per hour or distance is part of the objective. For further research of a case study it is recommended to consider which type of contracts for the vessel use are in place. Because for the fuel costs a decrease in distance traveled is desirable but if the vessel use is charged as fixed yearly costs or as a daily rate, this affects the development of a cost optimal schedule.

The OWSF model minimizes travel cost, the cost of a vessel staying offshore, and downtime cost. It does not consider technician cost. Moreover, it is assumed that there is a limitless number of technicians available and that there is no distinction in capabilities. The cost, availability and capability of technicians effects the optimal route and schedule. The limited availability of technicians limits the number of maintenance tasks that can be performed simultaneously. Depending on the method of payment for the technicians, the technician cost can influence the optimal route and schedule. If technicians are payed per hour, it can be unfavourable that the technicians stay at the vessel during the execution of tasks that they are not involved in. If the technicians are under full-time employment this occasion is not that relevant. The distinction in capabilities can prohibit the support of only one vessel for the execution of two tasks that require different capabilities, as it might exceed the technician capacity of the vessel. Especially in the combined maintenance of wind turbines and solar units it is very likely that technicians with different capabilities are required. Therefore, it is recommended to include the distinction between different technicians, the number of available technicians, and the costs of the technicians in the model to increase the accuracy of the model.

Furthermore, the OWSF model only considers required maintenance at the introduced nodes. The nodes represent the wind turbines and solar units. However, a wind and solar farm contains electricity infrastructure existing of submarine cables, transformers, and inverters. The maintenance of the electricity infrastructure not located at the wind turbine or solar unit is out of scope for this research. This is because the maintenance of the submarine electricity infrastructure requires often other vessels than the commonly used vessels for wind turbine maintenance, namely a cable laying vessel or a diving support vessel [47].

Only the most common types of maintenance support vessels are considered in the OWSF model. In addition to a CTV and SOV, an helicopter is often used in the maintenance support of offshore installations. The helicopter is not included because it is often used for unforeseen events and not included in the designed routes and schedule [96]. For the utilization of an SOV is assumed that the SOV can stay at the turbine in between shifts, during the night. However, when an SOV is in between shifts it is located at a save distance from the wind turbines [15]. An other assumption in the employment of the vessels in the model is that CTVs and SOVs can access the solar units. The current design of the floating solar units does not include a compatible landing platform. When maintenance is executed offshore it is supported by RHIBs. However, this research provides part of the information required to determine the necessity of such a landing platform for CTVs and SOVs at floating solar units.

The OWSF model is developed for research purposes. The applicability for different OWSFs is taken into account in the development of the model. Features are included in the model that are not required for the case study but might be needed for other case studies. Nevertheless, the required computational time and capacity limitations make the model unsuitable for operational purposes. Implementing a heuristic solution method can decrease the computational time significantly [71]. Research is needed to reduce the required memory for running the model.

The OWSF is applied to a case study to investigate the optimal route and schedule of maintenance support vessels of an offshore wind and solar farm. The case study involves as well assumptions and limitations. The case study concerns a virtual OWSF based on an operational offshore wind farm in the Dutch North sea; Prinses Amalia Windpark (PAWP). To simplify the study the virtual OWSF consists of six wind turbines and two floating solar units. Despite that the distance between the wind turbines and solar units is based on the size of the PAWP, the virtual wind farm is too small to represent a realistic OWSF. The number of wind turbines and solar units and the size of the total farm influences the number of required maintenance tasks and the distances between the turbines or units that require maintenance. More maintenance tasks with shorter distances in between could give incentive to combine the transport. The maintenance tasks are based on general knowledge of wind farm maintenance and expectations for offshore floating solar maintenance. Real time data of required maintenance tasks will give better insight in the optimal route and schedule of maintenance support vessels for an OWSF.

An other limitation of the case study is that the weather windows are based on the first hour and the last hour of the day that meets the required weather conditions. If during the work shift weather conditions get worse and then get better again it is ignored by the OWSF model. This can results in smaller or less weather windows than in reality. For further research it is recommended to analyse the weather data to detect the fluctuations of the weather conditions to be able to apply realistic weather windows.

Furthermore, only four shifts in February and May are analysed with required maintenance tasks according to knowledge of offshore wind farm maintenance and expectations of offshore floating solar panel maintenance. However, different combinations of required maintenance and different weather conditions can result in a different optimal route and schedule of the maintenance support vessels. Therefore, it is recommended to analyse more different scenarios and extent the range of required maintenance tasks to determine whether integrating the maintenance support for offshore wind turbines and offshore floating solar will decrease the travel and downtime costs.

Bibliography

[1] M. Lopez, N. Rodriguez, and G. Iglesias. “Combined Floating Offshore Wind and Solar PV”. In: *Journal of Marine Science and Engineering* 8.8 (July 2020), p. 576. DOI: 10.3390/jmse8080576.

[2] ESMAP World Bank Group and SERIS. “Where Sun Meets Water : Floating Solar Handbook for Practitioners”. In: *Washington, DC: World Bank* (2019).

[3] G.J.W. Van Brussel and W.A.A.M. Bierbooms. “Analysis of different means of transport in the operation and maintenance strategy for the reference DOWEC offshore wind farm”. In: *PROC OW EMES, Naples* (2003), pp. 1–12.

[4] T. A. T. Nguyen and S. Chou. “Maintenance strategy selection for improving cost-effectiveness of offshore wind systems”. In: 157 (Feb. 2018), pp. 86–95. DOI: 10.1016/j.enconman.2017.11.090.

[5] P. Zhou and P. T. Yin. “An opportunistic condition-based maintenance strategy for offshore wind farm based on predictive analytics”. In: *Renewable and Sustainable Energy Reviews* 109 (2019), pp. 1–9. DOI: https://doi.org/10.1016/j.rser.2019.03.049.

[6] N. Raknes et al. “Scheduling of Maintenance Tasks and Routing of a Joint Vessel Fleet for Multiple Offshore Wind Farms”. In: *Journal of Marine Science and Engineering* 5.1 (Feb. 2017), p. 11. DOI: 10.3390/jmse5010011.

[7] United Nations. *The Paris Agreement*. Accessed on 26-07-2021. URL: https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement.

[8] M. Rosa-Clot and G.M. Tina. “Current Status of FPV and Trends”. In: *Floating PV Plants*. Elsevier, 2020, pp. 9–18. DOI: 10.1016/b978-0-12-817061-8.00002-6.

[9] J. Van Zalk and P. Behrens. “The spatial extent of renewable and non-renewable power generation: A review and meta-analysis of power densities and their application in the U.S.” In: *Energy Policy* 123 (Dec. 2018), pp. 83–91. DOI: 10.1016/j.enpol.2018.08.023.

[10] N. D. A. Thi. “The Evolution of Floating Solar Photovoltaics”. In: *Research Gate: Berlin, Germany* (2017).

[11] L. Liu et al. “Power Generation Efficiency and Prospects of Floating Photovoltaic Systems”. In: *Energy Procedia* 105 (May 2017), pp. 1136–1142. DOI: 10.1016/j.egypro.2017.03.483.

[12] M. Houwing, N. Chrysochoidis-Astos, and E. Wiggelinkhuizen. “Multi Criteria Analysis for the electrical integration of floating offshore solar parks with offshore wind parks”. In: *TNO* (Apr. 2021).

[13] S. Oliveira-Pinto and J. Stokkermans. “Assessment of the potential of different floating solar technologies – Overview and analysis of different case studies”. In: *Energy Conversion and Management* 211 (May 2020), p. 112747. DOI: 10.1016/j.enconman.2020.112747.

[14] S. Oliveira-Pinto and J. Stokkermans. “Marine floating solar plants: an overview of potential, challenges and feasibility”. In: *Proceedings of the Institution of Civil Engineers - Maritime Engineering* 173.4 (Dec. 2020), pp. 120–135. DOI: 10.1680/jmaen.2020.10.

[15] A. Dewan and M. Asgarpour. “Reference O&M Concepts for Near and Far Offshore Wind Farms”. In: *ECN* (Dec. 2016). ECN-E—16-055.

[16] M. Shafiee. “Maintenance logistics organization for offshore wind energy: Current progress and future perspectives”. In: 77 (May 2015), pp. 182–193. DOI: 10.1016/j.renene.2014.11.045.

[17] H. Abdollahzadeh, K. Atashgar, and M. Abbasi. “Multi-objective opportunistic maintenance optimization of a wind farm considering limited number of maintenance groups”. In: *Renewable Energy* 88 (Apr. 2016), pp. 247–261. DOI: 10.1016/j.renene.2015.11.022.

[18] Y. Dalgic et al. “Advanced logistics planning for offshore wind farm operation and maintenance activities”. In: *Ocean Engineering* 101 (June 2015), pp. 211–226. DOI: 10.1016/j.oceaneng.2015.04.040.

[19] Y. Dalgic, I. Lazakis, and O. Turan. “Investigation of Optimum Crew Transfer Vessel Fleet for Offshore Wind Farm Maintenance Operations”. In: *Wind Engineering* 39.1 (Feb. 2015), pp. 31–52. DOI: 10.1260/0309-524x.39.1.31.

[20] Y. Dalgic et al. “Investigation of optimum jack-up vessel chartering strategy for offshore wind farm O&M activities”. In: *Ocean Engineering* 95 (Feb. 2015), pp. 106–115. DOI: 10.1016/j.oceaneng.2014.12.011.

[21] A. Erguido et al. “A dynamic opportunistic maintenance model to maximize energy-based availability while reducing the life cycle cost of wind farms”. In: *Renewable Energy* 114 (Dec. 2017), pp. 843–856. DOI: 10.1016/j.renene.2017.07.017.

[22] C. A. Irawan et al. “Simulation-based optimisation for stochastic maintenance routing in an offshore wind farm”. In: *European Journal of Operational Research* 289.3 (Mar. 2019), pp. 912–926. DOI: 10.1016/j.ejor.2019.08.032.

[23] X. Li et al. “A decision support system for strategic maintenance planning in offshore wind farms”. In: *Renewable Energy* 99 (Dec. 2016), pp. 784–799. DOI: 10.1016/j.renene.2016.07.037.

[24] R. Martin et al. “Sensitivity analysis of offshore wind farm operation and maintenance cost and availability”. In: *Renewable Energy* 85 (Jan. 2016), pp. 1226–1236. DOI: 10.1016/j.renene.2015.07.078.

[25] B. R. Sarker and T. I. Faiz. “Minimizing maintenance cost for offshore wind turbines following multi-level opportunistic preventive strategy”. In: *Renewable Energy* 85 (Jan. 2016), pp. 104–113. DOI: 10.1016/j.renene.2015.06.030.

[26] P. Wang et al. “The Effect of the Superhydrophobic Film on the Generation Efficiency of Photovoltaic Modules Affected by Salt-Containing Dust Deposition”. In: 9.6 (Nov. 2019), pp. 1727–1732. DOI: 10.1109/jphotov.2019.2930909.

[27] C. Zhang et al. “Opportunistic maintenance strategy for wind turbines considering weather conditions and spare parts inventory management”. In: *Renewable Energy* 133 (Apr. 2019), pp. 703–711. DOI: 10.1016/j.renene.2018.10.076.

[28] Z. Y. Zhang. “Scheduling and Routing Optimization of Maintenance Fleet for Offshore Wind Farms Using Duo-ACO”. In: *Advanced Materials Research* 1039 (Oct. 2014), pp. 294–301. DOI: 10.4028/www.scientific.net/amr.1039.294.

[29] Lijuan Dai, Magnus Stålhane, and Ingrid B. Utne. “Routing and Scheduling of Maintenance Fleet for Offshore Wind Farms”. In: *Wind Engineering* 39.1 (Feb. 2015), pp. 15–30. DOI: 10.1260/0309-524x.39.1.15.

[30] R. Dawid, D. McMillan, and M. Revie. “Heuristic algorithm for the problem of vessel routing optimisation for offshore wind farms”. In: *The Journal of Engineering* 2017.13 (Jan. 2017), pp. 1159–1163. DOI: 10.1049/joe.2017.0511.

[31] A. Gutierrez-Alcoba et al. “On offshore wind farm maintenance scheduling for decision support on vessel fleet composition”. In: *European Journal of Operational Research* 279.1 (Nov. 2019), pp. 124–131. DOI: 10.1016/j.ejor.2019.04.020.

[32] C. A. Irawan et al. “Optimisation of maintenance routing and scheduling for offshore wind farms”. In: *European Journal of Operational Research* 256.1 (Jan. 2017), pp. 76–89. DOI: 10.1016/j.ejor.2016.05.059.

[33] A. H. Schrotenboer et al. “Coordinating technician allocation and maintenance routing for offshore wind farms”. In: *Computers & Operations Research* 98 (Oct. 2018), pp. 185–197. DOI: 10.1016/j.cor.2018.05.019.

[34] M. Stålhane, L. M. Hvattum, and V. Skaar. “Optimization of Routing and Scheduling of Vessels to Perform Maintenance at Offshore Wind Farms”. In: *Energy Procedia* 80 (2015), pp. 92–99. DOI: 10.1016/j.egypro.2015.11.411.

[35] C. Stock-Williams and S. K. Swamy. "Automated daily maintenance planning for offshore wind farms". In: *Renewable Energy* 133 (Apr. 2019), pp. 1393–1403. DOI: 10.1016/j.renene.2018.08.112.

[36] I. Lazakis and S. Khan. "An optimization framework for daily route planning and scheduling of maintenance vessel activities in offshore wind farms". In: *Ocean Engineering* 225 (Apr. 2021), p. 108752. DOI: 10.1016/j.oceaneng.2021.108752.

[37] D. Fan et al. "A hybrid heuristic optimization of maintenance routing and scheduling for offshore wind farms". In: *Journal of Loss Prevention in the Process Industries* 62 (Nov. 2019), p. 103949. DOI: 10.1016/j.jlp.2019.103949.

[38] B. Puruncajas, Y. Segui, and C. Tutivén Gálvez. "Vibration-Response-Only Structural Health Monitoring for Offshore Wind Turbine Jacket Foundations via Convolutional Neural Networks". In: *Sensors* 20 (June 2020), p. 3429. DOI: 10.3390/s20123429.

[39] C . C. Tiangco. "Regional Knowledge and Support Thechnical Assistance Afghanistan, Azerbaijan, Kyrgyz Republic". In: *Floating Solar Prospects in Central and West Asia*. ADB. URL: https://www.adb.org/sites/default/files/am-content/412146/Annual%20Meeting%20_%20Floating%20Solar_FPV%20C_Tiangco%20Sanitized.pdf.

[40] *North Sea 1 Offshore Solar Project*. Accessed on 26.05.2021. URL: https://oceansofenergy.blue/north-sea-1/.

[41] *Projects - recent solar energy installations by Swimsol*. Accessed on 26.05.2021. Sept. 2019. URL: https://swimsol.com/solar-projects-offshore-solarsea-and-rooftop/.

[42] *OUR PRODUCTS*. Accessed on 04.05.2021. URL: https://oceansun.no/our-products/.

[43] A. Bhambhani. *5 MW Offshore Floating PV Farm Online*. Accessed on 26.05.2021. URL: http://taiyangnews.info/business/5-mw-offshore-floating-pv-farm-online/.

[44] D. Wagenaar. *PV magazine: Off-shore PV project with LCOE of €0.15/kwh off the Belgian coast*. Sept. 2021. URL: https://oceansofenergy.blue/2021/09/06/pv-magazine-off-shore-pv-project-with-lcoe-of-e0-15-kwh-off-the-belgian-coast/.

[45] GL Garrad Hassan. "A Guide to UK Offshore Wind Operations and Maintenance". In: *Scottisch Enterprise and The Crown Estate* (2013).

[46] H. van de Pieterman R. P.and Braam. "ECN O&M Calculator User Manual Version 3". In: *ECN* ECN-X–17-118 (2017).

[47] R. P. van de Pieterman et al. "Optimisation of maintenance strategies for offshore wind farms A case study performed with the OMCE-Calculator". In: *ECN* (Dec. 2011). ECN-M–11-103.

[48] *Allegro*. Accessed on 02.04.2021. URL: https://www.4coffshore.com/vessels/vessel-allegro-vid3823.html.

[49] *ABB to equip high-spec service operations vessel for the world's largest offshore wind farm*. Accessed on 06.04.2021. May 2018. URL: https://new.abb.com/news/detail/51620/abb-to-equip-high-spec-service-operations-vessel-for-the-worlds-largest-offshore-wind-farm.

[50] *9 mtr. Professional Offshore Support RIB for sale or charter*. Accessed on 01.06.2021. Mar. 2020. URL: https://www.novi-marine.com/boot/9-mtr-professional-offshore-support-rib-for-sale-or-charter/.

[51] A. Allal et al. "Multi-agent based simulation-optimization of maintenance routing in offshore wind farms". In: *Computers & Industrial Engineering* 157 (July 2021), p. 107342. DOI: 10.1016/j.cie.2021.107342.

[52] S. Raff. "Routing and scheduling of vehicles and crews: The state of the art". In: *Computers & Operations Research* 10.2 (Jan. 1983), pp. 63–211. DOI: 10.1016/0305-0548(83)90030-8.

[53] G. B. Dantzig and J. H. Ramser. "The Truck Dispatching Problem". In: *Management Science* 6.1 (Oct. 1959), pp. 80–91. DOI: 10.1287/mnsc.6.1.80.

[54] M. M. Flood. "The Traveling-Salesman Problem". In: *Operations Research* 4.1 (Feb. 1956), pp. 61–75. DOI: 10.1287/opre.4.1.61.

[55] E. W. Weisstein. “Traveling Salesman Problem”. In: *Mathword - A Wolfram Web Resource* (). URL: https://mathworld.wolfram.com/TravelingSalesmanProblem.html.

[56] G. Laporte. “What you should know about the vehicle routing problem”. In: *Naval Research Logistics* 54.8 (2007), pp. 811–819. DOI: 10.1002/nav.20261.

[57] G. Dantzig, R. Fulkerson, and S. Johnson. “Solution of a Large-Scale Traveling-Salesman Problem”. In: 2.4 (Nov. 1954), pp. 393–410. DOI: 10.1287/opre.2.4.393.

[58] F. Besnard et al. “An optimization framework for opportunistic maintenance of offshore wind power system”. In: IEEE, June 2009. DOI: 10.1109/ptc.2009.5281868.

[59] F. Besnard et al. “A stochastic model for opportunistic maintenance planning of offshore wind farms”. In: *2011 IEEE Trondheim PowerTech*. IEEE, June 2011. DOI: 10.1109/ptc.2011.6019376.

[60] F. Besnard, K. Fischer, and L. B. Tjernberg. “A Model for the Optimization of the Maintenance Support Organization for Offshore Wind Farms”. In: *IEEE Transactions on Sustainable Energy* 4.2 (Apr. 2013), pp. 443–450. DOI: 10.1109/tste.2012.2225454.

[61] E. E. Halvorsen-Weare et al. “Vessel Fleet Analysis for Maintenance Operations at Offshore Wind Farms”. In: 35 (2013), pp. 167–176. DOI: 10.1016/j.egypro.2013.07.170.

[62] C. Gundegjerde et al. “A stochastic fleet size and mix model for maintenance operations at offshore wind farms”. In: 52 (Mar. 2015), pp. 74–92. DOI: 10.1016/j.trc.2015.01.005.

[63] M. Stålhane et al. “Vessel Fleet Optimization for Maintenance Operations at Offshore Wind Farms Under Uncertainty”. In: 94 (Sept. 2016), pp. 357–366. DOI: 10.1016/j.egypro.2016.09.195.

[64] G. B. Dantzig and P. Wolfe. “Decomposition Principle for Linear Programs”. In: 8.1 (Feb. 1960), pp. 101–111. DOI: 10.1287/opre.8.1.101.

[65] R. Dawid, D. McMillan, and M. Revie. “Development of an O&M tool for short term decision making applied to offshore wind farms”. In: *WindEurope Summit 2016* (2016). URL: https://strathprints.strath.ac.uk/58072/.

[66] H. Z. TAN et al. “Modeling and Solution of Offshore Wind Farm Maintenance Scheduling”. In: *DEStech Transactions on Environment, Energy and Earth Science* seee (Mar. 2017). DOI: 10.12783/dteees/seee2016/6527.

[67] J-F. Cordeau et al. “A guide to vehicle routing heuristics”. In: *Journal of the Operational Research Society* 53.5 (May 2002), pp. 512–522. DOI: 10.1057/palgrave.jors.2601319.

[68] G. Laporte and Y. Nobert. “Exact Algorithms for the Vehicle Routing Problem”. In: *Surveys in Combinatorial Optimization*. Elsevier, 1987, pp. 147–184. DOI: 10.1016/s0304-0208(08)73235-3.

[69] D. Pecin et al. “Improved branch-cut-and-price for capacitated vehicle routing”. In: *Mathematical Programming Computation* 9.1 (June 2016), pp. 61–100. DOI: 10.1007/s12532-016-0108-8.

[70] J. Alonso-Mora et al. “On-demand high-capacity ride-sharing via dynamic trip-vehicle assignment”. In: *Proceedings of the National Academy of Sciences* 114.3 (Jan. 2017), pp. 462–467. DOI: 10.1073/pnas.1611675114.

[71] M. H. J. Romanycia and F. J. Pelletier. “What is a heuristic?” In: *Computational Intelligence* 1.1 (Jan. 1985), pp. 47–58. DOI: 10.1111/j.1467-8640.1985.tb00058.x.

[72] G. Clarke and J. W. Wright. “Scheduling of Vehicles from a Central Depot to a Number of Delivery Points”. In: *Operations Research* 12.4 (Aug. 1964), pp. 568–581. DOI: 10.1287/opre.12.4.568.

[73] B. E. Gillett and L. R. Miller. “A Heuristic Algorithm for the Vehicle-Dispatch Problem”. In: *Operations Research* 22.2 (Apr. 1974), pp. 340–349. DOI: 10.1287/opre.22.2.340.

[74] M. A. Novak. “The Pickup and Delivery Problem with Split Loads”. In: (2005).

[75] S. Lin. “Computer Solutions of the Traveling Salesman Problem”. In: *Bell System Technical Journal* 44.10 (Dec. 1965), pp. 2245–2269. DOI: 10.1002/j.1538-7305.1965.tb04146.x.

[76] G. Laporte et al. “Classical and modern heuristics for the vehicle routing problem”. In: *International Transactions in Operational Research* 7.4-5 (Sept. 2000), pp. 285–300. DOI: 10.1111/j.1475-3995.2000.tb00200.x.

[77] K. Braekers, K. Ramaekers, and I. Van Nieuwenhuyse. “The vehicle routing problem: State of the art classification and review”. In: *Computers & Industrial Engineering* 99 (Sept. 2016), pp. 300–313. DOI: 10.1016/j.cie.2015.12.007.

[78] F. Glover. “Future paths for integer programming and links to artificial intelligence”. In: *Computers & Operations Research* 13.5 (Jan. 1986), pp. 533–549. DOI: 10.1016/0305-0548(86)90048-1.

[79] I. H. Osman. “Metastrategy simulated annealing and tabu search algorithms for the vehicle routing problem”. In: *Annals of Operations Research* 41.4 (Dec. 1993), pp. 421–451. DOI: 10.1007/bf02023004.

[80] P. Hao et al. “Intra-platoon vehicle sequence optimization for eco-cooperative adaptive cruise control”. In: IEEE, Oct. 2017. DOI: 10.1109/itsc.2017.8317879.

[81] S. Kirkpatrick, C. D. Gelatt, and M. P. Vecchi. “Optimization by Simulated Annealing”. In: *Science* 220.4598 (May 1983), pp. 671–680. DOI: 10.1126/science.220.4598.671.

[82] K. Rose, E. Gurewitz, and G. Fox. “A deterministic annealing approach to clustering”. In: *Pattern Recognition Letters* 11.9 (Sept. 1990), pp. 589–594. DOI: 10.1016/0167-8655(90)90010-y.

[83] M. Yasuda. “Deterministic Annealing: A Variant of Simulated Annealing and its Application to Fuzzy Clustering”. In: *Computational Optimization in Engineering - Paradigms and Applications*. InTech, Apr. 2017. DOI: 10.5772/66072.

[84] B. M. Baker and M. A. Ayechew. “A genetic algorithm for the vehicle routing problem”. In: *Computers & Operations Research* 30.5 (Apr. 2003), pp. 787–800. DOI: 10.1016/s0305-0548(02)00051-5.

[85] A. Colorni, M. Dorigo, and V. Maniezzo. “Distributed optimization by ant colonies.” In: *Proceedings of the first European conference on artificial life* 142 (Dec. 1991), pp. 134–142.

[86] B. Bullnheimer, R.F. Hartl, and C. Strauss. In: *Annals of Operations Research* 89 (1999), pp. 319–328. DOI: 10.1023/a:1018940026670.

[87] C. Shin and M. Lee. “Swarm-Intelligence-Centric Routing Algorithm for Wireless Sensor Networks”. In: 20.18 (Sept. 2020), p. 5164. DOI: 10.3390/s20185164.

[88] V. K. Ojha, A. Abraham, and V. Snášel. “Metaheuristic design of feedforward neural networks: A review of two decades of research”. In: *Engineering Applications of Artificial Intelligence* 60 (Apr. 2017), pp. 97–116. DOI: 10.1016/j.engappai.2017.01.013.

[89] S. Ropke and D. Pisinger. “An Adaptive Large Neighborhood Search Heuristic for the Pickup and Delivery Problem with Time Windows”. In: 40.4 (Nov. 2006), pp. 455–472. DOI: 10.1287/trsc.1050.0135.

[90] B.H. Bulder, E.T.G. Bot, and G. Bedon. “Scoping analysis of the potential yield of the Hollandse Kust (noord) wind farm and the influence on the existing wind farms in the proximity”. In: *ECN* (Apr. 2018).

[91] Solargis. URL: https://globalsolaratlas.info/detail?c=52.456009%5C%2C4.611511%5C%2C9&s=52.84923%5C%2C3.666687&m=site&pv=hydro%5C%2C180%5C%2C10%5C%2C6000.

[92] *Specifications*. URL: https://www.actamarine.com/our_fleet/download_specs.

[93] URL: https://www.royalihc.com/-/media/royalihc/products/offshore-wind/factsheet-sov-t6018.pdf.

[94] Ministerie van Defensie. *RHIB-Motorboot*. Jan. 2022. URL: https://www.defensie.nl/onderwerpen/materieel/schepen/rhib-motorboot.

[95] R. Dawid, D. McMillan, and M. Revie. “Time series semi-Markov decision process with variable costs for maintenance planning”. In: *Risk, Reliability and Safety: Innovating Theory and Practice*. CRC Press, Sept. 2016, pp. 1145–1150. DOI: 10.1201/9781315374987-172.

[96] B. Hu, P. Stumpf, and W. vd Deijl. “Offshore Wind Access 2019”. In: *TNO* (2019).

Routing and scheduling of maintenance support vessels for an offshore wind and solar farm

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Floating photovoltaic (FPV) is an emerging concept. Potential is recognized in combining FPV and offshore wind farms to create an offshore wind and solar farm. One of the remaining uncertainties around the potential of an offshore wind and solar farm is the value of the operations and maintenance cost. As one of the main contributing factors to operations and maintenance costs of offshore wind farms is the accessibility, integration of the transport for maintenance of the wind turbines and solar units can minimize the costs. By means of a route and scheduling optimization tool the optimal route and schedule of maintenance support vessels for a virtual OWSF is investigated. The research indicates that the optimal route and schedule of maintenance support vessels for a virtual OWSF does not include integration of the transport. The main reason is the low costs of an RHIB compared to the cost of a CTV or SOV. However, the optimal route and schedule is very case dependent. Thus recommended is to apply the model to multiple case studies to form a general conclusion.

Routing and scheduling | Offshore wind farm maintenance | Offshore floating solar maintenance | Offshore wind and solar farm

Introduction

The Paris Agreement, signed by 194 states and the European Union, has the purpose to limit the temperature increase in response to the global climate change threat. In order to limit the global warming, countries aim to reach global peaking of greenhouse gas emissions as soon as possible (1). The ongoing energy transition is one of the efforts to limit the greenhouse gas emission. It induces a shift from carbon-based to renewable sources for energy generation. According to Rosa-Clot and Tina (2) multiple analysis are performed to predict the continuation of the energy transition. They all converge to a few concepts including the expectation that renewable energy sources will provide 80% of the full electric energy production with solar and wind sources both leading in the electric energy production. A drawback of wind and solar energy harnessing is the irregularity of the sources which complicates the grid integration. Another important drawback is the amount of area needed to meet the electricity demand. The average power density of solar and wind technologies (7 W/m^2 and 3 W/m^2 resp.) are much lower than the average energy density of non-renewable energy generation technologies (307 W/m^2) (3).

The land scarcity, especially in Europe, has lead to development of offshore wind farms that are now operating successfully. Furthermore, the interest floating solar in the form of floating photo voltaic (FPV) has increased. Several FPV installations on inland water bodies are in operation already (4). In addition to the advantage of avoiding land occupation, FPV installations have the benefit of the cooling effect of the water. Therefore, a higher efficiency is achieved with FPV than with land-based photo voltaic systems (5). So for both wind and solar energy harnessing, locating the farms offshore has benefits. And by combining the solar and wind energy generation offshore an increased power output per unit surface area and a reduction in the temporal variability of the output would be realised compared to non-hybrid energy harnessing farms. In addition, the electricity infrastructure can be combined for the wind and solar facilities, thereby reduce construction costs.(6)

The potential of FPV and the benefit of combining wind and solar have lead to the interest in an offshore wind and solar farm (OWSF). Research is being conducted on the electrical integration of the wind and solar installations (7) and the optimal design of offshore FPV (8)(9). One of the remaining uncertainties around the feasibility of an OWSF is the operations and maintenance (O&M) cost (10). O&M of offshore wind farms is well developed, but is still facing important challenges. O&M costs accounts for 25% of the life cycle costs of offshore wind farms. Revenue losses and downtime account for 25% of the O&M costs (11). An important contributor to the revenue losses and downtime is accessibility. Small weather windows due to the combination of bad weather conditions and regulations, especially safety regulations, decrease accessibility and therefore decrease the availability of the wind farm (12). O&M support strategies are being investigated for offshore wind farms that make better use of the weather windows and vessel transfers possible. O&M support consists of the logistic operations that make sure that the personnel, equipment and spare parts are at the right place at the right time. Nguyen et al. (13) and Zhou et al. (14) showed that an improved O&M support strategy can reduce the O&M cost with 4.56% and 39.24% respectively. As offshore floating solar will likewise face challenges in accessibility due to the combination of bad weather conditions and safety regulations, it will as well require an optimal O&M support strategy.

The largest part of O&M support for offshore wind farms is the logistic operation for the maintenance tasks (13). Therefore, this research focuses on the logistic aspect of the maintenance operation i.e. the offshore maintenance support. In an OWSF the most immediate question is: Should the maintenance support of the wind turbines and floating solar units be integrated? Because the maintenance support of operational offshore wind farms is already existing, the organization could include the maintenance of the floating solar units. In order to find the answer for this question research is needed to analyse the advantages and disadvantages of combining the maintenance support of wind and solar at operational level, i.e. in the routing and scheduling of the vessels.

This research aims to develop an optimal route and schedule of the maintenance support vessels for an OWSF. The maintenance of the wind and solar installations can be addressed separately as the units differ in many respects. However, it is expected that combining the offshore logistics of the wind and solar maintenance tasks will be advantageous because of the high cost of the operation and small time windows due to weather conditions. Combining the maintenance support has the potential to increase the effective use of the time windows and the vessel transfers. For this reason, the maintenance support of an OWSF is addressed as one operation with focus on the routing and scheduling of the vessels. The research question of this research is: *What is the optimal route and schedule of maintenance support vessels for an offshore integrated wind and solar farm?*

Method

The optimal route and schedule of the maintenance support vessel for an OWSF is established by means of an route and scheduling optimization model. Because an OWSF is a new concept, no maintenance support vessel routing and scheduling optimization model is developed yet. However, a substantial amount of research is conducted to develop a maintenance support vessel routing and scheduling optimization model for offshore wind farms. Since the maintenance of the offshore FPV is expected to face similar challenges, the developed models for offshore wind farms is used as the base for developing the optimization model for routing and scheduling maintenance support vessels for an OWSF. The different mathematical formulations in the literature for offshore wind farms are assessed on which requirements for an OWSF are included. The mathematical problem formulated in the research of Raknes et al. (15) includes most of the requirements for representing the maintenance support vessel routing and scheduling problem for OWSFs (See figure 1).

When the mathematical representation of the problem is formulated a solution method is applied to find the optimal solution. Figure 2 gives an overview of the described solution

	Dai et al. (2015) [28]	Stålhane et al. (2015) [34]	Dawid et al. (2016) [63]	Tan et al. (2017) [64]	Irawan et al. (2017) [31]	Raknes et al. (2017) [32]	Schrotenboer et al. (2018) [33]	Lazakis et al. (2021) [36]	Allal et al. (2021) [49]
Maintenance tasks are allocated to different nodes	v	v	v		v	v		v	v
Multiple vessels with different routes	v	v	v	v	v	v	v	v	v
Different characteristics for vessels						v	v	v	
Multiple services orders per tour			v	v				v	v
Downtime cost related to the maintenance task				v		v			v
Downtime cost related to weather conditions				v		v			v
Distinction between preventive and corrective maintenance tasks	v				v	v	v	v	
number of ticks	3	2	3	4	3	6	3	5	5

Fig. 1. Assessment of the mathematical formulations

methods applied to offshore wind farm vessel routing and scheduling problems. Exact methods provide an 100 percent accurate solution but require more computational time than meta-heuristics solution methods. Meta-heuristic solution methods provide less accurate solutions. They exist of complex mathematical algorithms, and are therefore harder to apply. Accuracy and applicability are more important as the research aims for an accurate solution and the solution method should be applicable for solving the chosen mathematical formulation of the optimization problem. The chosen mathematical formulation is based on mixed integer programming (MIP) with an extensive number of constraints. Gurobi is proven to be an effective commercial mixed integer programming (MIP) applicable for a wide range of routing and scheduling problems and easy to implement. Therefore, Gurobi is chosen as solution method for this research.

	Zhang (2014) [27]	Stalhane et al. (2015) [34]	Irawan et al. (2017) [31]	Raknes et al. (2017) [32]	Schrotenboer et al. (2018) [33]	Stock-Williams and Swamy (2019) [35]	Fan et al. (2019) [37]	Lazakis et al. (2021) [35]	Allal et al. (2021) [49]	Gurobi
Solution method (Exact (E)/ Meta-heuristics (M))	M	M	E	E	M	M	M	M	M	E
Method	Duo-ACO	Labelling	Dantzig-Wolfe decomposition	Rolling horizon heuristics	2-ALNS	GA	MPSO + DWPs	Multiple consecutive unconventional heustics	ACS	Branch-and-cut algorithm

Fig. 2. Summary of solution methods applied for maintenance support vessel routing and scheduling for offshore wind farms

The mathematical model of Raknes et al. (15) is formulated for the maintenance support of multiple wind farms from one depot. It is a static and deterministic routing and scheduling problem for a short planning period formulated as a mixed integer programming (MIP) model. The planning period exists of multiple shifts. One shift represents a working day of 8 hours. The routing in the model consists of two levels. The first level is the routing of the vessels between wind farms and the depot and the second level is the routing of vessels within the wind farm. The routing between wind farms is considered as a graph where each wind farm is represented by one node and the depot by two nodes; a start and an end node. In the graph, the arcs between the nodes are associated to travelling times and travelling costs. The second level, the routing between wind turbines, is not considered as a graph. The turbines that require maintenance are represented by the maintenance tasks and the location of the turbines are ignored. The average travel time between the turbines in the wind farm is added to the task duration. The maintenance tasks consist of delivery tasks and pick-up tasks, which represent the drop-off and pick-up of technicians by the vessel. The model includes a target amount of performed preventive maintenance tasks in the planning period. Furthermore, the model makes distinction between performed tasks and completed tasks. A performed task in a shift is executed but not completed during the shift. A completed task is finished in during that shift. The model incorporates SOV's, called an accommodation vessel (AV) in the model, that can stay at the wind farm for multiple shifts and CTV's that depart from the depot at the start of a shift when the weather conditions allow it.

In order to make the mathematical problem applicable to optimize the maintenance support of an OWSF, multiple adjustments are made. The model of Raknes et al. lacks the ability to perform multiple service orders per tour. This requirement is assessed as not included because the model can only perform multiple maintenance tasks allocated to the same note. This limitation is due to the fact that in the model of Raknes et al. the nodes represent wind farms. It would be unrealistic that a vessel performs maintenance tasks at different wind farms during the same shift. Therefore, the first adjustment required to make the model applicable for this research is that the nodes represent units (wind or solar) in stead of wind farms. In the model of Raknes et al. it is possible to allocate different maintenance tasks to different nodes. Therefore, the next required adjustment is to enable the vessels to visit multiple nodes during one shift. Furthermore, the model of Raknes et al. considers multiple types of vessels with different characteristics. A set of RHIBs is added to the input and in order to include the third type of vessels some small adjustments are required. Figure 3 shows a representation of the routing and scheduling model for an OWSF.

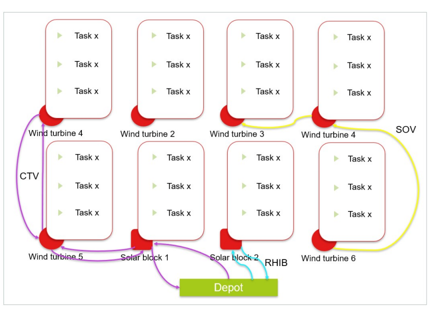

Fig. 3. Representation of the routing and scheduling model for an OWSF

The mathematical model of the maintenance support vessel routing and scheduling optimization for an OWSF is presented and explained beneath.

Indices

- i, j — Nodes (wind turbines, floating solar units, and depot)
- m, n, l — Maintenance tasks
- k — Type of maintenance tasks
- v — Vessels
- s — Shifts

Sets

- N^W — All wind turbine and solar unit nodes, $N^W = \{1, 2..., |N^W|\}, N^W \subset N$
- N — All nodes, $N = \{0, 1, 2, ..., (|N^W|+1)\}$. Nodes $i \in \{1, 2, ..., |N^W|\}$ are wind turbines or solar units and nodes $i \in \{0, (|N^W|+1)\}$ represent the depot
- K — All maintenance task types
- M — All maintenance tasks including both delivery tasks and pick-up tasks, $M = \{0, 1, 2, ..., |M|\}$
- M^- — All delivery tasks (representing the actual maintenance tasks), $M^- = \{1, 2, ..., |M^-|\}, M^- \subset M$
- M_i^- — All delivery tasks at wind farm i, $i \in N^W, M_i^- \subseteq M^-$
- M_{ik}^- — All delivery tasks of type k at wind farm i, $i \in N^W, k \in K, M_{ik}^- \subseteq M_i^-$
- M^+ — All pick-up tasks $M^+ = \{(|M^-|+1), (|M^-|+2), ..., (2|M^-|)\}, M^+ \subset M$
- M_i^+ — All pick-up tasks at wind farm $i, i \in N^W, M_i^+ \subseteq M^+$
- M^C — All corrective maintenance tasks, $M^C \subseteq M^-$
- M^P — All preventive maintenance tasks, $M^P \subseteq M^-$
- V — All vessels
- V^A — All AVs, $V^A \subseteq V$
- V^C — All CTVs, $V^C \subseteq V$
- V^R — All RHIBs, $V^C \subseteq V$
- V_m — All vessels that can perform maintenance task $m, V_m \subseteq V$
- V_m^A — All AVs that can perform maintenance task $m, V_m^A = V_m \cap V^A$
- V_m^C — All CTVs that can perform maintenance task $m, V_m^C = V_m \cap V^C$
- V_m^R — All CTVs that can perform maintenance task $m, V_m^C = V_m \cap V^C$
- S — All shifts of the planning period
- S^0 — All shifts of the planning period, including the last shift of the previous planning period, shift 0

Constants

- T_{ijv}^T — Transportation time between node $i \in N$ and node $j \in N$ for vessel $\in V$
- T_m^{MT} — Duration of task $m \in M^-$
- T^{PD} — Time to transfer technicians from vessel to turbine and from turbine to vessel (transfer time)
- D_v^{START} — Number of shifts a vessel $v \in V^A$ has been offshore when the planning period starts
- D_v^{LIMIT} — Number of shifts a vessel $v \in V^A$ can stay offshore without returning to the depot
- P_{iv}^{START} — 1 if vessel $v \in V^A$ is located at node $i \in N$ at the start of the planning period, 0 otherwise
- T^{DAY} — Number of time units in a day
- T_s^{SHIFT} — Length of shift $s \in S$
- T^{MIN} — Minimum length of weather window in a shift for a CTV to leave the depot during the shift
- T^{MINt} — Minimum time a maintenance task should be performed

L_{vs}^{W} Lower bound for the weather window of vessel $v \in V$ in shift $s \in S$

U_{vs}^{W} Upper bound for the weather window of vessel $v \in V$ in shift $s \in S$

B The desired number of preventive maintenance tasks to be completed during the planning period

R_{ms} 1 if all necessary spare parts and equipment for performing task $m \in M^-$ are available in shift $s \in S$, 0 otherwise

E_m 1 if task m requires that the vessel performing the task is located at the turbine while the task is being performed, 0 otherwise

Q_v Technician capacity of vessel $v \in V$

P_m Number of technicians needed to perform task $m \in M$, positive for delivery tasks and negative for pick-up tasks

C_{ijv}^{T} Transportation costs between node $i \in N$ and node $j \in N$ for vessel $v \in V$

C_{ms}^{LP} Downtime costs per time unit during shift $s \in S$ due to loss of production when shutting down the turbine or solar unit where maintenance task $m \in M^-$ is located

C_{v}^{OUT} The cost for vessel $v \in V^A$ to stay offshore between two shifts

C_{v}^{IT} The average internal transportation cost for vessel $v \in V$ to travel to a maintenance task $m \in M^-$ inside a wind farm

C_{m}^{NP} The penalty cost per shift of not completing a preventive maintenance task during the planning period

C_{m}^{NC} The penalty cost per shift of not completing a corrective maintenance task during the planning period

C_{m}^{NP*} The penalty cost per time unit of remaining work for a preventive maintenance task $m \in M^P$ that is not completed within the planning period

C_{m}^{NC*} The penalty cost per time unit of remaining work for a corrective maintenance task $m \in M^C$ that is not completed within the planning period

K_{ms} 1 if the energy production during shift $s \in S$ is below a specified limit for when to perform $m \in M^- \cap M^P$ as extra preventive maintenance, 0 otherwise

δ Small value greater than zero

Decision variables

x_{mvs} 1 if vessel $v \in V_m$ is used to perform maintenance task $m \in M$ during shift $s \in S$, 0 otherwise

y_{ijvs} 1 if vessel $v \in V$ travels directly between node $i \in N$ and $j \in N, i \neq j$, during shift $s \in S$, 0 otherwise

z_{mnvs} 1 if vessel $v \in V_m \cap V_n$ performs maintenance task $n \in M$ directly after maintenance task $m \in M$ during shift $s \in S$, 0 otherwise

w_{ivs} 1 if vessel $v \in V^A$ stays at node $i \in N$ between shift $s \in S$ and $(s+1) \in S$, 0 otherwise

t_{mvs} The time vessel $v \in V_m$ starts maintenance task $m \in M$ during shift $s \in S$

l_{ms} Time counter for how long the turbine or solar unit where maintenance task $m \in M^-$ is located is shut down during shift $s \in S$. The time counter for shift s starts at 0 when the shift starts and reaches its maximum at the beginning of the next shift, $s+1$

c_m The penalty cost of a task $m \in M^-$ that is not completed during the planning period

p_{mvs} The number of technicians at vessel $v \in V_m$ immediately after visiting the turbine of task $m \in M$ during shift $s \in S$

f_{ms} 1 if task $m \in M^-$ is completed before the end of shift $s \in S$ (during shift s or during earlier shifts than s), 0 otherwise

Objective function

$$\min Z = \sum_{i \in N} \sum_{j \in N} \sum_{v \in V} \sum_{s \in S} C_{ijv}^{T} y_{ijvs}, \quad \textbf{(1a)}$$

$$+ \sum_{i \in N^W} \sum_{v \in V_m} \sum_{s \in S} C_{v}^{OUT} w_{ivs}, \quad \textbf{(1b)}$$

$$+ \sum_{m \in M^-} \sum_{s \in S} C_{ms}^{LP} l_{ms}, \quad \textbf{(1c)}$$

$$+ \sum_{m \in M^P} \sum_{s \in S} C_{m}^{NP} (1 - f_{ms}), \quad \textbf{(1d)}$$

$$+ \sum_{m \in M^C} \sum_{s \in S} C_{m}^{NC} (1 - f_{ms}), \quad \textbf{(1e)}$$

$$+ \sum_{m \in M^-} c_m \quad \textbf{(1f)}$$

The objective function of the optimization problem minimizes the total cost. Sub-equation 1a considers the internal transport costs within a wind farm, based on the performed tasks and the average transportation time between turbines in the farm. AV's can stay offshore for multiple shifts, these costs are represented by 1b. During certain maintenance tasks it is required that the turbine is shut down. The production loss during shut down is taken into account as downtime cost in 4.1c and varies per shift according to the weather expectations. In addition to the real costs, penalty costs are included. Sub-equation 1d and 1e apply penalty costs for not completing a task during a shift for preventive and corrective tasks respectively. These parts of the objective function ensure that the respective tasks are completed within a shift if there is free vessel capacity. There is also an encouragement to work on tasks for which there is insufficient time to complete them during the planning period, if there is free vessel capacity. A penalty cost for each task that is not completed based on how much time there is left of the task at the end of the planning period is added in 1f

The constraints of the the routing and scheduling problem of Raknes et al. are grouped as it is grouped in (15). It consists of constraints concerning flow of CTVs and RHIBs, flow of AVs, execution of tasks, time management, precedence of tasks, downtime, technicians balances and the domain of the decision variables.

Constraints for the flow of CTVs:

$$\sum_{j\in N} y_{0jvs} = 1, \qquad v \in V^C \cup V^R, s \in S \tag{2}$$

$$\sum_{i\in N} y_{i|N|vs} = 1, \qquad v \in V^C \cup V^R, s \in S \tag{3}$$

$$y_{0|N|vs} = 1, \qquad v \in V^C \cup V^R, \; s \in S|(U^W_{vs} - L^W_{vs}) < T^{MIN} \tag{4}$$

$$\sum_{i\in N} y_{ijvs} = \sum_{i\in N} y_{jivs}, \quad j \in N^W, v \in V^C \cup V^R, s \in S \tag{5}$$

Constraint 2 ensures that each CTV and RHIB leaves the start depot node,$i = 0$, during each shift. Constraint 3 makes sure that each CTV and RHIB ends at the end depot node, $i = |N|$, during each shift. A CTV or RHIB may not leave the depot during a shift where the weather window is shorter than a specified minimum duration. This is prevented by constraint 4 by forcing the CTV and RHIB to go straight from beginning node to end node which represent both the same depot. Constraint 5 ensures that when a CTV and RHIB visits a node it also leaver the node during the same shift.

Constraints for the flow of AVs:

$$w_{iv(s-1)} + \sum_{j\in N} y_{jivs} = \sum_{j\in N} y_{ijvs} + w_{ivs}, \quad i \in N^W, v \in V^A, s \in S^0 \backslash \{0\} \tag{6}$$

$$\sum_{j\in N} y_{0jvs} = w_{|N|v(s-1)}, \qquad v \in V^A, s \in S^0 \backslash \{0\} \tag{7}$$

$$w_{|N|vs} = \sum_{j\in N} y_{j|N|vs}, \qquad v \in V^A, s \in S \tag{8}$$

$$w_{iv0} = P^{START}_{iv}, \qquad i \in N, v \in V^A \tag{9}$$

$$\sum_{i\in N^W} \sum_{s=1}^{D^{LIMIT}_v - D^{START}_v} y_{i|N|vs} \geq 1, \quad v \in V^A | D^{LIMIT}_v - D^{START}_v \leq |S| \tag{10}$$

Because AVs are equipped to accommodate personnel for longer periods and therefor can stay offshore for multiple shifts, the node flow of AVs is differently handled. Constraint 6 ensures that an AV located at a wind farm at the beginning of a shift either leaves the wind farm at the end of the sift or stays there until the next shift. Constraint 7 handles that an AV can only leave the depot during a shift if it was located at the depot at the end of the previous shift. If the AV travels to the depot during a shift, constraint 8 makes sure that the AV stays at the depot until the next shift. At the beginning of a planning period an AV can be located at a wind farm already according to P^{START}_{iv}. This is taken into account by constraint 9. The period an AV can stay offshore is limited by constraint 10.

Constraints for the execution of tasks:

$$\sum_{v\in V_m} x_{mvs} \leq 1, \qquad m \in M^-, s \in S \tag{11}$$

$$x_{mvs} = 1, \qquad v \in V^C \cup V^R, \; m = 0 \cup |M|, s \in S \tag{12}$$

$$x_{0vs} = w_{|N|v(s-1)}, \qquad v \in V^A, s \in S^0 | s > 0 \tag{13}$$

$$x_{|M|vs} = w_{|N|vs}, \qquad v \in V^A, s \in S \tag{14}$$

$$x_{mvs} \leq \sum_{j\in N} y_{jivs}, \qquad i \in N^W, m \in M^-_i \cup M^+_i, \; v \in V^C_m, s \in S \tag{15}$$

$$x_{mvs} \leq \sum_{j\in N} y_{jivs} + w_{iv(s-1)} - \sum_{j\in N} y_{ijvs}, \quad i \in N^W, m \in M^-_i \cup M^+_i, v \in V^A_m, s \in S \tag{16}$$

Constraint 11 handles the requirement that each task is performed by maximum one vessel each shift. The CTVs and RHIBs start at the depot. Therefore, constraint 12 makes sure the depot task is performed by each vessel during each shift. AVs can start from an offshore location at one of the wind farms. For this reason, constraint 13 ensures that the start depot task is performed by an AV that is located at the depot and constraint 14 ensures the same for the end depot task. In the model of Raknes et al. the nodes represent the wind farms and the tasks of the wind turbines in the farm are associated with the wind farm node. Constraint 15 restricts that a task m at wind farm i can only be performed by CTV v if v is located at i during the shift. Constraint 16 concerns this restriction for AVs.

$$x_{mvs} = x_{(m+|M^-|)vs}, \qquad m \in M^-, v \in V_m, s \in S \tag{17}$$

$$\sum_{v\in V^m} x_{mvs} = 0, \qquad m \in M^-, s \in S | R_{ms} = 0 \tag{18}$$

$$\sum_{m\in M^P} \sum_{v\in V_m} x_{mvs} \leq B, \quad s \in S | K_{ms} = 0 \tag{19}$$

A delivery and pick-up task at the same turbine must be performed by the same vessel. This is ensured by constraint 17. Constraint 18 prohibits performing a task during a shift for which $R_{ms} = 0$, which means that the task is not ready to be performed in that shift. In the model there is a desired number of preventive maintenance tasks to be performed per shift in addition to the corrective maintenance tasks. Extra preventive maintenance tasks can be performed if there is time or capacity left during the shift. However, constraint 19 makes sure that if the energy production is higher than a specified limit, the number of performed preventive tasks does not exceed the desired number of preventive tasks.

$$T_m^{MT} - \sum_{v \in V_m} \sum_{h=1}^{s} (t_{(m+|M^-|)vh} - t_{mvh} - T^{PD} x_{mvh}) + (T_s^{SHIFT} - T^{PD}) f_{ms} \geq \delta, \quad m \in M^-, s \in S \quad \textbf{(20)}$$

$$\sum_{v \in V_m} \sum_{h=1}^{s} (t_{(m+|M^-|)vh} - t_{mvh} - T^{PD} x_{mvh}) \geq T_m^{MT} f_{ms}, \quad m \in M^-, s \in S \quad \textbf{(21)}$$

$$\sum_{v \in V_m} x_{mvs} \leq 1 - f_{m(s-1)}, \quad m \in M^-, s \in S \backslash \{1\} \quad \textbf{(22)}$$

The constraints above (equation 20 till 22) handle the variables that indicate in which shifts each task is completed. f_{ms} becomes one by means of constraint 20 if task m is completed within shift s. f_{ms} is forced to zero by constraint 21 if task m is not completed within shift s. Constraint 22 restricts that a task m is executed during shift s after the task is completed.

$$c_m \geq C_m^{NC*} (T_m^{MT} - \sum_{v \in V_m} \sum_{s \in S} (t_{(m+|M^-|)vs} - t_{mvs} - T^{PD} x_{mvs})), \quad m \in M^C \cap M^- \quad \textbf{(23)}$$

$$c_m \geq C_m^{NP*} (T_m^{MT} - \sum_{v \in V_m} \sum_{s \in S} (t_{(m+|M^-|)vs} - t_{mvs} - T^{PD} x_{mvs})), \quad m \in M^P \cap M^- \quad \textbf{(24)}$$

Constraints 23 and 24 determine the penalty costs for uncompleted tasks according to the remaining required time for the task, for corrective and preventive tasks respectively. Both constraints are based on the difference between task duration and the time between the drop-off and pick-up tasks minus the transfer time. The remaining task time is multiplied by a cost per time unit for that particular task.

Constraints for time management

$$t_{mvs} \leq T_s^{SHIFT} x_{mvs}, \quad m \in M, v \in V_m, s \in S \quad \textbf{(25)}$$

$$t_{mvs} \geq L_{vs}^W \sum_{j \in N} y_{jivs} - T_s^{SHIFT}(1 - x_{mvs}), \quad i \in N^W, m \in M_i^-, v \in V_m^C, s \in S \quad \textbf{(26)}$$

$$t_{mvs} \geq \sum_{j \in N} T_{jiv}^T y_{jivs} - T_s^{SHIFT}(1 - x_{mvs}), \quad i \in N^W, m \in M_i^-, v \in V_m^C, s \in S \quad \textbf{(27)}$$

$$t_{mvs} \geq L_{vs}^W (\sum_{j \in N} y_{jivs} + w_{iv(s-1)}) - T_s^{SHIFT}(1 - x_{mvs}), \quad i \in N^W, m \in M_i^-, v \in V_m^A, s \in S \quad \textbf{(28)}$$

$$t_{mvs} \geq T_{0iv}^T y_{0ivs} - T_s^{SHIFT}(1 - x_{mvs}), \quad i \in N^W, m \in M_i^-, v \in V_m^A, s \in S \quad \textbf{(29)}$$

$$t_{mvs} + T^{PD} x_{mvs} \leq U_{vs}^W, \quad m \in M^+, v \in V_m, s \in S \quad \textbf{(30)}$$

Constraint 25 ensures that the start time of task m is set to zero if the task is not performed. The start time of drop-off tasks must be greater than or equal to both the lower bound of the weather window and the travel time to the wind farm. This is taken care of by constraint 26 and 27 respectively. For AVs, constraint 28 ensures that start time of the drop-off tasks is great than of equal to the lower bound of the weather window. The start time of drop-off tasks performed by an AV must be greater than or equal to the travel time from the depot to the wind farm is the AV starts the shift at the depot (see constraint 29). Constraint 30 makes sure that pick-up tasks start in time in order to be able to transfer the technicians before the upper bound of the weather window.

$$t_{(m+|M^-|)vs} \geq t_{mvs} + T^{PD} x_{mvs}, \quad m \in M^-, v \in V_m, s \in S \quad \textbf{(31)}$$

$$t_{mvs} - t_{nvs} + \delta \leq T_s^{SHIFT}(1 - z_{mnvs}), \quad i \in N^W, m \in M_i^- \cup M_i^+, n \in M_i^- \cup M_i^+, v \in V_m \cap V_n, s \in S | m \neq n \quad \textbf{(32)}$$

$$t_{mvs} - t_{|M|vs} + T^{PD} x_{mvs} + T_{i|n|v}^T y_{i|N|vs} \leq T_s^{SHIFT}(1 - z_{m|M|vs}), \quad i \in N^W, m \in M_i^- \cup M_i^+, v \in V_m \cap V_n, s \in S \quad \textbf{(33)}$$

$$t_{mvs} - t_{nvs} + T^{PD} + T_{jiv}^T y_{jivs} \leq T_s^{SHIFT}(1 - z_{mnvs}), \quad i \in N^W, j \in N^W, m \in M_j^- \cup M_j^+, n \in M_i^- \cup M_i^+, v \in V_m \cap V_n, s \in S | m \neq n \quad \textbf{(34)}$$

The pick-up tasks should be performed after the drop-off task plus the transfer time. This is handled by constraint 31. The time between the start times of consecutive tasks must be greater than or equal to the sum of the average travel time between turbines and the transfer time (see constraint 32). Constraint 33 ensures that the time between the start times of the end depot task and the previous task must be greater than the sum of the transfer time and the travel time between the last wind farm and the depot. The time between the start times of consecutive tasks that must be performed on different units should be greater than or equal to the travel time between the units and the transfer time. Therefore, constraint 34 is added to the constraints for time management.

Constraints for the precedence of tasks

$$x_{mvs} = \sum_{n \in M \backslash \{0\}} z_{mnvs} \qquad m \in M \backslash \{|M|\}, v \in V_m^C \cap V_n^C, \; s \in S \tag{35}$$

$$x_{mvs} = \sum_{n \in M \backslash \{|M|\}} z_{nmvs} \qquad m \in M \backslash \{|0|\}, v \in V_m^C \cap V_n^C, \; s \in S \tag{36}$$

$$x_{mvs} = \sum_{n \in M \backslash \{0\}} z_{mnvs} \qquad m \in M \backslash \{|M|\}, v \in V_m^R \cap V_n^R, \; s \in S \tag{37}$$

$$x_{mvs} = \sum_{n \in M \backslash \{|M|\}} z_{nmvs} \qquad m \in M \backslash \{|0|\}, v \in V_m^R \cap V_n^R, \; s \in S \tag{38}$$

$$x_{mvs} \geq \sum_{n \in M \backslash \{0\}} z_{mnvs} \qquad m \in M \backslash \{|M|\}, v \in V_m^A \cap V_n^A, \; s \in S \tag{39}$$

$$x_{mvs} \geq \sum_{n \in M \backslash \{|M|\}} z_{nmvs} \qquad m \in M \backslash \{|0|\}, v \in V_m^A \cap V_n^A, \; s \in S \tag{40}$$

$$\sum_{m \in M \backslash \{|M|\}} \sum_{n \in M \backslash \{0\}} z_{mnvs} \geq \sum_{m \in M} x_{mvs} - 1, \qquad v \in V_m^A \cap V_n^A, s \in S \tag{41}$$

$$t_{nvs} x_{mvs} \geq t_{(m+|N|)vs} x_{nvs}, \qquad i,j \in N^W, m \in M_i, \; n \in M_j, v \in V_m \cap V_n, \; s \in S | i \neq j, E_m = 1 \tag{42}$$

$$z_{mnvs} \leq y_{jivs}, \qquad m \in M_j^- \cup M_j^+, \; n \in M_i^- \cup M_i^+, i,j \in N, \; v \in V_m \cap V_n, s \in S | i \neq j \tag{43}$$

For the precedence of tasks performed by CTVs, constraints 35 and 36 make sure that each task has a previous and a following task except for the depot tasks. The same applies for RHIBs (see constraints 37 and 38). Constraints 39 and 40 ensure that the tasks performed by AVs have maximum one previous and following task except for the depot tasks. As an AV can stay offshore, the first or last maintenance tasks at wind farms do not have a previous or following task if the AV stayed or stays offshore. To make sure that the rest of the tasks do have a previous and following task constraint 41 states that the number of consecutive tasks must be minimal as much as the number of performed tasks minus one. Constraint 42 ensures that for tasks that require the vessel to stay, subsequent tasks at other turbines or solar units can be started after this task is finished. If consecutive tasks are performed at different turbines or solar units the vessel must travel between the units. Therefore constraint 43 is added to the constraints of precedence.

Constraints for the downtime

$$l_{ms} \geq T^{DAY}(1 - f_{ms}), \qquad m \in M^C, s \in S \tag{44}$$

$$l_{ms} \geq \sum_{v \in V_m} (t_{(m+|M^-|)vs} + T^{PD} x_{mvs}) - T_s^{SHIFT}(1 - (f_{ms} - f_{m(s-1)})), \qquad m \in M^C, s \in S \backslash \{1\} \tag{45}$$

$$l_{ms} \geq \sum_{v \in V_m} (t_{(m+|M^-|)vs} + T^{PD} x_{mvs}) - T_s^{SHIFT}(1 - f_{ms}), \qquad m \in M^C, s = 1 \tag{46}$$

For corrective tasks the downtime starts at the beginning of the planning period. If the task is not performed during a shift constraint 44 forces the time counter of the downtime to be greater than or equal to the number of time units in one day. When a task is completed in a shift, constraint 45 restricts the time counter to stop after the technicians are picked-up and transferred to the vessel. Constraints 46 does the same but for the first shift of the planning period, as this shift has no preceding shift.

$$l_{ms} \geq \sum_{v \in V_m} (t_{(m+|M^-|)vs} + T^{PD} x_{mvs} - t_{mvs}), \qquad m \in M^P, s \in S \tag{47}$$

$$\sum_{v \in V_m} (t_{(m+|M^-|)vs} + T^{PD} x_{mvs} - t_{mvs}) \geq T^{MINt} x_{mvs}, \qquad m \in M^P, s \in S \tag{48}$$

For preventive tasks the turbines are only shut down during the maintenance tasks. Constraint 47 makes sure that the downtime is minimal as much as the time between the start of the drop-off task till the moment that the technicians are transferred back to the vessel. Constraint 48 avoids that the technicians are left at the turbine for a time period that is so short that they in reality do not have time to perform any maintenance. This is avoided by means of a minimal time for preventive maintenance tasks.

Constraints for the balance of technicians:

$$p_{mvs} - P_n - p_{nvs} \leq (Q_v - P_n)(1 - z_{mnvs}),$$
$$m \in M \backslash \{|M|\}, n \in M \backslash \{0\}, v \in V_m \cap V_n, s \in S \quad \textbf{(49)}$$

$$p_{mvs} - P_n - p_{nvs} \geq (-P_n - Q_v)(1 - z_{mnvs}),$$
$$m \in M \backslash \{|M|\}, n \in M \backslash \{0\}, v \in V_m \cap V_n, s \in S \quad \textbf{(50)}$$

Constrained 49 and 50 are linearized constraints that ensure the balance of technicians for consecutive tasks m and n that are performed respectively. The constraints state that the number of technicians on the vessel directly after task n must be equal to the sum of the number of technicians directly after task m and the number of technicians required for task n.

$$p_{mvs} \leq (Q_v - P_m)x_{mvs}, \quad m \in M^-, v \in V_m, s \in S \quad \textbf{(51)}$$
$$p_{mvs} \leq Q_v x_{mvs}, \quad m \in M^+, v \in V_m, s \in S \quad \textbf{(52)}$$
$$p_{mvs} \geq -P_m x_{mvs}, \quad m \in M^+, v \in V_m, s \in S \quad \textbf{(53)}$$
$$p_{mvs} \leq Q_v x_{mvs}, \quad m = \{0\} \cup m = \{|M|\}, v \in V_m, s \in S \quad \textbf{(54)}$$
$$p_{mvs} \geq (Q_v - P_m)x_{mvs}, \quad m \in M^-, v \in V_m, s \in S | E_m = 1 \quad \textbf{(55)}$$

Constaints 51 until 55 make sure that the vessel capacity is never exceeded.

The domains of the decision variable

$$x_{mvs} \in [0,1], \quad m \in M, v \in V_m, s \in S \quad \textbf{(56)}$$
$$y_{ijvs} \in [0,1], \quad i, j \in N, v \in V, s \in S, i \neq j \quad \textbf{(57)}$$
$$z_{mnvs} \in [0,1], \quad i \in N^W, m, n \in M_i, v \in V_m \cap V_n, s \in S \quad \textbf{(58)}$$
$$w_{ivs} \in [0,1], \quad i \in N, v \in V^A, s \in S \quad \textbf{(59)}$$
$$f_{mvs} \in [0,1], \quad m \in M, v \in V_m, s \in S \quad \textbf{(60)}$$
$$t_{mvs} \geq 0, \quad m \in M, v \in V, s \in S \quad \textbf{(61)}$$
$$l_{ms} \geq 0, \quad m \in M, s \in S \quad \textbf{(62)}$$
$$p_{mvs} \geq 0, integer, \quad m \in M, v \in V_m, s \in S \quad \textbf{(63)}$$
$$c_m \geq 0, integer, \quad m \in M \quad \textbf{(64)}$$

Constraints 56 until 64 determine the domains of the decision variables.

The OWSF model is applied to a case study in order to find the optimal route and schedule of maintenance support vessels for an OWSF. At the moment no offshore wind and solar farm is in operation. Therefore, the case study is applied to a virtual wind and solar farm. In order to approach reality the virtual scenario is based on an operating wind farm, namely The Prinses Amaliawindpark in the Dutch North Sea. The wind farm is in operation since 2008. It is located 23 km from its maintenance port IJmuiden and contains 60 turbines. The virtual wind and solar farm has the same location and distance to its maintenance port as the Prinses Amaliawindpark. It consists of six wind turbines and two floating solar units. The location of the wind turbines and solar blocks is based on the average distance between the wind turbines in the Prinses Amaliawindpark (see figure 4).

Figure 4 shows the layout of the virtual wind and solar farm. The turbines and solar units are equally divided over the area of the Prinses Amaliawindpark. The defined nodes of the solar units represent the location where the technicians can access the solar unit from the vessel.

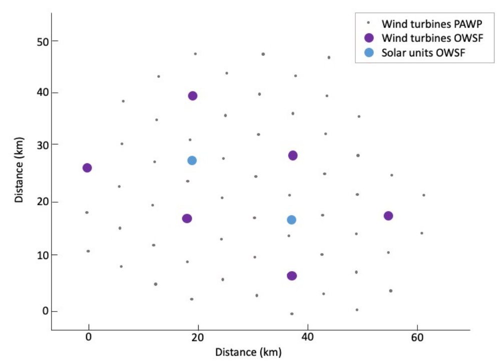

Fig. 4. Layout of virtual wind and solar farm based on the layout of Prinses Amaliawindpark

The case study analysis Two scenarios; in May and in February. May is a month with low wind speeds. Therefore, regular preventive maintenance of offshore wind turbines is often performed in May. February is a month with high wind speeds. The weather conditions result in limited weather windows for maintenance. Therefore, it is assumed that only corrective maintenance is performed in February. Accordingly, the required maintenance is determined for the two scenarios. The data and information required for the wind turbines and solar units is extracted from an ongoing research at TNO. The weather conditions are determined from the weather data of the Prinses Amaliawindpark in 2014. This data does not include solar radiation data. Therefore, average estimated solar radiation at the Dutch North Sea according to is (16) used. The two scenarios consists of the first 4 shifts of the month and include 3 CTVs, 1 SOV, and 1 RHIB.

Results

The case study shows that the optimal route and schedule of maintenance support vessels for an OWSF includes no integration between the support for the maintenance of the wind turbines and for the solar units. The maintenance of the solar units is performed with separate transport than the maintenance of the wind turbines.

Further analysis of the case study indicates that whether it is cost optimal to use an RHIB or CTV for the maintenance of solar units is closely related to the cost speed ratio of the vessel types. For this analysis the February scenario is taken as base, because it includes various short maintenance tasks which gives more combinations of maintenance tasks that can be supported by the same vessel than for the May scenario. To analyse the cost dependency multiple simulations are performed with only varying the cost of the use of an RHIB. In the same way the speed dependency is analysed but than only varying the speed of an RHIB. Figure 5 shows the tipping point for when an RHIB is included in the optimal route and schedule for the case study related to the cost of an RHIB. Figure 6 shows the tipping point related to the speed on the RHIB. The tipping points can be explained by the following mathematical relation. Where C_{RHIB} and C_{CTV} are the cost in euro per hour of an RHIB and CTV respectively and v_{RHIB} and v_{CTV} are the speed in kilometer per hour of an RHIB and CTV respectively. This means that for this scenario the inclusion of an RHIB is only dependent of the cost and speed difference between the vessel types.

$$C_{RHIB} = \frac{C_{CTV}}{v_{CTV}} v_{RHIB} \tag{65}$$

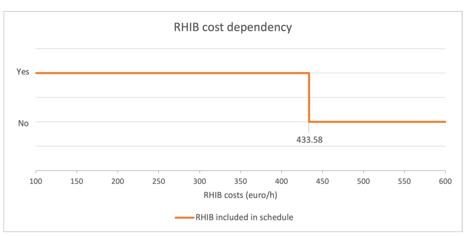

Fig. 5. The effect of the cost of an RHIB on the inclusion of an RHIB in the schedule

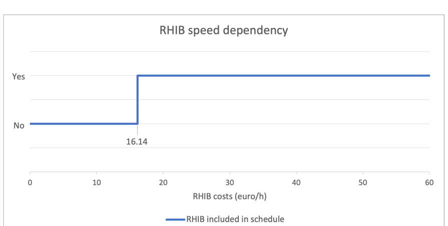

Fig. 6. The effect of the speed of an RHIB on the inclusion of an RHIB in the schedule

Conclusion

This research aims to develop an optimal route and schedule of the maintenance support vessels for an OWSF. The main research question is *What is the optimal route and schedule of maintenance support vessels for an offshore integrated wind and solar farm?* The results of the case study show that the optimal route and schedule of maintenance support vessels of an OWSF includes separate trips to the turbines and solar units. This result indicates that integrating the maintenance support for offshore wind turbines and offshore floating solar does not decrease the travel and downtime costs. This contradicts the expectation that combining the maintenance support would increase the effective use of the time windows and the vessel transfers. The choice of using an RHIB for the solar unit maintenance and therefor not integrating the transport with the wind turbine maintenance transport is mainly because of the use of an RHIB is much cheaper than the use of a CTV or SOV. The low costs of using an RHIB for the solar unit maintenance appears to out way the potential cost reduction of sharing the transport.

Discussion

The discussion points of this research can be divided in two categories: Limitations of the OWSF model and limitations of the case study.

Assumptions made in the development of the model and limitations of the model are:

- The required maintenance is known at beginning of the planning period.
- The travel costs are specified per path between two nodes. The fixed costs of the vessels are converted into costs per path between nodes.
- Technician capabilities and costs are not included.
- Required maintenance that is not allocated to wind turbine or solar unit nodes is excluded.
- Only the most common type of maintenance per component failure is considered.
- The high computational time and capacity limitations make the model unsuitable for operational purposes.

Limitations of the case study are:

- The required maintenance is only determined from general knowledge of offshore wind farm maintenance and expectations of offshore floating solar panel maintenance.
- Weather windows are based on the weather conditions of the first and last hour of a shift. The weather conditions in between are neglected.
- The availability of technicians, spare parts, and equipment is not included.

It is recommended to consider above limitations and assumptions for further research.

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Bibliography

1. United Nations. The paris agreement. Accessed on 26-07-2021.
2. M. Rosa-Clot and G.M. Tina. Current status of FPV and trends. In *Floating PV Plants*, pages 9–18. Elsevier, 2020. doi: 10.1016/b978-0-12-817061-8.00002-6.
3. J. Van Zalk and P. Behrens. The spatial extent of renewable and non-renewable power generation: A review and meta-analysis of power densities and their application in the u.s. *Energy Policy*, 123:83–91, dec 2018. doi: 10.1016/j.enpol.2018.08.023.
4. N. D. A. Thi. The evolution of floating solar photovoltaics. *Research Gate: Berlin, Germany*, 2017.
5. L. Liu, Q. Wang, H. Lin, L. Li, Q. Sun, and R. Wennersten. Power generation efficiency and prospects of floating photovoltaic systems. *Energy Procedia*, 105:1136–1142, may 2017. doi: 10.1016/j.egypro.2017.03.483.
6. M. Lopez, N. Rodriguez, and G. Iglesias. Combined floating offshore wind and solar PV. *Journal of Marine Science and Engineering*, 8(8):576, July 2020. doi: 10.3390/jmse8080576.
7. M. Houwing, N. Chrysochoidis-Astos, and E. Wiggelinkhuizen. Multi criteria analysis for the electrical integration of floating offshore solar parks with offshore wind parks. *TNO*, April 2021.
8. S. Oliveira-Pinto and J. Stokkermans. Assessment of the potential of different floating solar technologies – overview and analysis of different case studies. *Energy Conversion and Management*, 211:112747, may 2020. doi: 10.1016/j.enconman.2020.112747.
9. S. Oliveira-Pinto and J. Stokkermans. Marine floating solar plants: an overview of potential, challenges and feasibility. *Proceedings of the Institution of Civil Engineers - Maritime Engineering*, 173(4):120–135, dec 2020. doi: 10.1680/jmaen.2020.10.
10. ESMAP World Bank Group and SERIS. Where sun meets water : Floating solar handbook for practitioners. *Washington, DC: World Bank*, 2019.
11. A. Dewan and M. Asgarpour. Reference o&m concepts for near and far offshore wind farms. *ECN*, December 2016. ECN-E—16-055.
12. G.J.W. Van Brussel and W.A.A.M. Bierbooms. Analysis of different means of transport in the operation and maintenance strategy for the reference dowec offshore wind farm. *PROC OW EMES, Naples*, pages 1–12, 2003.
13. T. A. T. Nguyen and S. Chou. Maintenance strategy selection for improving cost-effectiveness of offshore wind systems. 157:86–95, feb 2018. doi: 10.1016/j.enconman.2017.11.090.
14. P. Zhou and P. T. Yin. An opportunistic condition-based maintenance strategy for offshore wind farm based on predictive analytics. *Renewable and Sustainable Energy Reviews*, (109):1–9, 2019. doi: https://doi.org/10.1016/j.rser.2019.03.049.
15. N. Raknes, K. Ødeskaug, M. Stålhane, and L. Hvattum. Scheduling of maintenance tasks and routing of a joint vessel fleet for multiple offshore wind farms. *Journal of Marine Science and Engineering*, 5(1):11, feb 2017. doi: 10.3390/jmse5010011.
16. Solargis.

A

Mathematical formulation of the OWSF model

The mathematical model of the maintenance support vessel routing and scheduling optimization for an OWSF is presented and explained beneath.

Indices

i, j	Nodes (wind turbines, floating solar units, and depot)
m, n, l	Maintenance tasks
k	Type of maintenance tasks
v	Vessels
s	Shifts

Sets

N^W	All wind turbine and solar unit nodes, $N^W = \{1, 2..., \|N^W\|\}, N^W \subset N$
N	All nodes, $N = \{0, 1, 2, ..., (\|N^W\| + 1)\}$. Nodes $i \in \{1, 2, ..., \|N^W\|\}$ are items and nodes $i \in \{0, (\|N^W\| + 1)\}$ are the depot
K	All maintenance task types
M	All maintenance tasks including both delivery tasks and pick-up tasks, $M = \{0, 1, 2, ..., \|M\|\}$
M^-	All delivery tasks (representing the actual maintenance tasks), $M^- = \{1, 2, ..., \|M^-\|\}, M^- \subset M$
M_i^-	All delivery tasks at wind farm i, $i \in N^W, M_i^- \subseteq M^-$
M_{ik}^-	All delivery tasks of type k at wind farm i, $i \in N^W, k \in K, M_{ik}^- \subseteq M_i^-$
M^+	All pick-up tasks $M^+ = \{(\|M^-\| + 1), (\|M^-\| + 2), ..., (2\|M^-\|)\}, M^+ \subset M$
M_i^+	All pick-up tasks at wind farm $i, i \in N^W, M_i^+ \subseteq M^+$
M^C	All corrective maintenance tasks, $M^C \subseteq M^-$
M^P	All preventive maintenance tasks, $M^P \subseteq M^-$
V	All vessels
V^A	All AVs, $V^A \subseteq V$
V^C	All CTVs, $V^C \subseteq V$
V^R	All RHIBs, $V^C \subseteq V$
V_m	All vessels that can perform maintenance task $m, V_m \subseteq V$
V_m^A	All AVs that can perform maintenance task $m, V_m^A = V_m \cap V^A$
V_m^C	All CTVs that can perform maintenance task $m, V_m^C = V_m \cap V^C$
V_m^R	All CTVs that can perform maintenance task $m, V_m^C = V_m \cap V^C$
S	All shifts of the planning period
S^0	All shifts of the planning period, including the last shift of the previous planning period, shift 0

Constants

T^{T}_{ijv}	Transportation time between node $i \in N$ and node $j \in N$ for vessel $\in V$
T^{MT}_{m}	Duration of task $m \in M^{-}$
T^{PD}	Time to transfer technicians from vessel to turbine and from turbine to vessel (transfer time)
D^{START}_{v}	Number of shifts a vessel $v \in V^{A}$ has been offshore when the planning period starts
D^{LIMIT}_{v}	Number of shifts a vessel $v \in V^{A}$ can stay offshore without returning to the depot
P^{START}_{iv}	1 if vessel $v \in V^{A}$ is located at node $i \in N$ at the start of the planning period, 0 otherwise
T^{DAY}	Number of time units in a day
T^{SHIFT}_{s}	Length of shift $s \in S$
T^{MIN}	Minimum length of weather window in a shift for a CTV to leave the depot during the shift
T^{MINt}	Minimum time a maintenance task should be performed
L^{W}_{vs}	Lower bound for the weather window of vessel $v \in V$ in shift $s \in S$
U^{W}_{vs}	Upper bound for the weather window of vessel $v \in V$ in shift $s \in S$
B	The desired number of preventive maintenance tasks to be completed during the planning period
R_{ms}	1 if all necessary spare parts and equipment for performing task $m \in M^{-}$ are available in shift $s \in S$, 0 otherwise
E_{m}	1 if task m requires that the vessel performing the task is located at the turbine while the task is being performed, 0 otherwise
Q_{v}	Technician capacity of vessel $v \in V$
P_{m}	Number of technicians needed to perform task $m \in M$, positive for delivery tasks and negative for pick-up tasks
C^{T}_{ijv}	Transportation costs between node $i \in N$ and node $j \in N$ for vessel $v \in V$
C^{LP}_{ms}	Downtime costs per time unit during shift $s \in S$ due to loss of production when shutting down the turbine or solar unit where maintenance task $m \in M^{-}$ is located
C^{OUT}_{v}	The cost for vessel $v \in V^{A}$ to stay offshore between two shifts
C^{IT}_{v}	The average internal transportation cost for vessel $v \in V$ to travel to a maintenance task $m \in M^{-}$ inside a wind farm
C^{NP}_{m}	The penalty cost per shift of not completing a preventive maintenance task during the planning period
C^{NC}_{m}	The penalty cost per shift of not completing a corrective maintenance task during the planning period
C^{NP*}_{m}	The penalty cost per time unit of remaining work for a preventive maintenance task $m \in M^{P}$ that is not completed within the planning period
C^{NC*}_{m}	The penalty cost per time unit of remaining work for a corrective maintenance task $m \in M^{C}$ that is not completed within the planning period
K_{ms}	1 if the energy production during shift $s \in S$ is below a specified limit for when to perform $m \in M^{-} \cap M^{P}$ as extra preventive maintenance, 0 otherwise
δ	Small value greater than zero

Decision variables

x_{mvs}	1 if vessel $v \in V_{m}$ is used to perform maintenance task $m \in M$ during shift $s \in S$, 0 otherwise
y_{ijvs}	1 if vessel $v \in V$ travels directly between node $i \in N$ and $j \in N, i \neq j$, during shift $s \in S$, 0 otherwise
z_{mnvs}	1 if vessel $v \in V_{m} \cap V_{n}$ performs maintenance task $n \in M$ directly after maintenance task $m \in M$ during shift $s \in S$, 0 otherwise
w_{ivs}	1 if vessel $v \in V^{A}$ stays at node $i \in N$ between shift $s \in S$ and $(s+1) \in S$, 0 otherwise
t_{mvs}	The time vessel $v \in V_{m}$ starts maintenance task $m \in M$ during shift $s \in S$
l_{ms}	Time counter for how long the turbine or solar unit where maintenance task $m \in M^{-}$ is located is shut down during shift $s \in S$. The time counter for shift s starts at 0 when the shift starts and reaches its maximum at the beginning of the next shift, $s+1$
c_{m}	The penalty cost of a task $m \in M^{-}$ that is not completed during the planning period
p_{mvs}	The number of technicians at vessel $v \in V_{m}$ immediately after visiting the turbine of task $m \in M$ during shift $s \in S$
f_{ms}	1 if task $m \in M^{-}$ is completed before the end of shift $s \in S$ (during shift s or during earlier shifts than s), 0 otherwise

Objective function

$$\min Z = \sum_{i \in N} \sum_{j \in N} \sum_{v \in V} \sum_{s \in S} C^{T}_{ijv} y_{ijvs}, \tag{A.1a}$$

$$+ \sum_{i \in N^W} \sum_{v \in V_m} \sum_{s \in S} C^{OUT}_{v} w_{ivs}, \tag{A.1b}$$

$$+ \sum_{m \in M^-} \sum_{s \in S} C^{LP}_{ms} l_{ms}, \tag{A.1c}$$

$$+ \sum_{m \in M^P} \sum_{s \in S} C^{NP}_{m} (1 - f_{ms}), \tag{A.1d}$$

$$+ \sum_{m \in M^C} \sum_{s \in S} C^{NC}_{m} (1 - f_{ms}), \tag{A.1e}$$

$$+ \sum_{m \in M^-} c_m \tag{A.1f}$$

The objective function of the optimization problem minimizes the total cost. Sub-equation A.1a considers the internal transport costs within a wind farm, based on the performed tasks and the average transportation time between turbines in the farm. AV's can stay offshore for multiple shifts, these costs are represented by A.1b. During certain maintenance tasks it is required that the turbine is shut down. The production loss during shut down is taken into account as downtime cost in 4.1c and varies per shift according to the weather expectations. In addition to the real costs, penalty costs are included. Sub-equation A.1d and A.1e are penalty costs for not completing a task during a shift for preventive and corrective tasks respectively. These parts of the objective function ensure that the respective tasks are completed within a shift if there is free vessel capacity. There is also an encouragement to work on tasks for which there is insufficient time to complete them during the planning period, if there is free vessel capacity. A penalty cost for each task that is not completed based on how much time there is left of the task at the end of the planning period is added in A.1f

The constraints of the the routing and scheduling problem of Raknes et al. are grouped as it is grouped in [6]. It consists of constraints concerning flow of CTVs and RHIBs, flow of AVs, execution of tasks, time management, precedence of tasks, downtime, technicians balances and the domain of the decision variables.

Constraints for the flow of CTVs and RHIBs:

$$\sum_{j \in N} y_{0jvs} = 1, \qquad v \in V^C \cup V^R, s \in S \tag{A.2}$$

$$\sum_{i \in N} y_{i|N|vs} = 1, \qquad v \in V^C \cup V^R, s \in S \tag{A.3}$$

$$y_{0|N|vs} = 1, \qquad v \in V^C \cup V^R, s \in S | (U^W_{vs} - L^W_{vs}) < T^{MIN} \tag{A.4}$$

$$\sum_{i \in N} y_{ijvs} = \sum_{i \in N} y_{jivs}, \qquad j \in N^W, v \in V^C \cup V^R, s \in S \tag{A.5}$$

(A.6)

Constraint A.2 ensures that each CTV and RHIB leaves the start depot node, $i = 0$, during each shift. Constraint A.3 makes sure that each CTV and RHIB ends at the end depot node, $i = |N|$, during each shift. A CTV or RHIB may not leave the depot during a shift where the weather window is shorter than a specified minimum duration. This is prevented by constraint A.4 by forcing the CTV and RHIB to go straight from beginning node to end node which represent both the same depot. Constraint A.5 ensures that when a CTV and RHIB visits a node it also leaver the node during the same shift.

Constraints for the flow of AVs:

$$w_{iv(s-1)} + \sum_{j \in N} y_{jivs} = \sum_{j \in N} y_{ijvs} + w_{ivs}, \qquad i \in N^W, v \in V^A, s \in S^0 \backslash \{0\} \tag{A.7}$$

$$\sum_{j \in N} y_{0jvs} = w_{|N|v(s-1)}, \qquad v \in V^A, s \in S^0 \backslash \{0\} \tag{A.8}$$

$$w_{|N|vs} = \sum_{j \in N} y_{j|N|vs}, \qquad v \in V^A, s \in S \tag{A.9}$$

$$w_{iv0} = P_{iv}^{START}, \qquad i \in N, v \in V^A \tag{A.10}$$

$$\sum_{i \in N^W} \sum_{s=1}^{D_v^{LIMIT} - D_v^{START}} y_{i|N|vs} \geq 1, \qquad v \in V^A | D_v^{LIMIT} - D_v^{START} \leq |S| \tag{A.11}$$

Because AVs are equipped to accommodate personnel for longer periods and therefor can stay off-shore for multiple shifts, the node flow of AVs is differently handled. Constraint A.7 ensures that an AV located at a wind farm at the beginning of a shift either leaves the wind farm at the end of the sift or stays there until the next shift. Constraint A.8 handles that an AV can only leave the depot during a shift if it was located at the depot at the end of the previous shift. If the AV travels to the depot during a shift, constraint A.9 makes sure that the AV stays at the depot until the next shift. At the beginning of a planning period an AV can be located at a wind farm already according to P_{iv}^{START}. This is taken into account by constraint A.10. The period an AV can stay offshore is limited by constraint A.11.

Constraints for the execution of tasks:

$$\sum_{v \in V_m} x_{mvs} \leq 1, \qquad m \in M^-, s \in S \tag{A.12}$$

$$x_{mvs} = 1, \qquad v \in V^C \cup V^R, m = 0 \cup |M|, s \in S \tag{A.13}$$

$$x_{0vs} = w_{|N|v(s-1)}, \qquad v \in V^A, s \in S^0 | s > 0 \tag{A.14}$$

$$x_{|M|vs} = w_{|N|vs}, \qquad v \in V^A, s \in S \tag{A.15}$$

$$x_{mvs} \leq \sum_{j \in N} y_{jivs}, \qquad i \in N^W, m \in M_i^- \cup M_i^+, v \in V_m^C, s \in S \tag{A.16}$$

$$x_{mvs} \leq \sum_{j \in N} y_{jivs} + w_{iv(s-1)} - \sum_{j \in N} y_{ijvs}, \qquad i \in N^W, m \in M_i^- \cup M_i^+, v \in V_m^A, s \in S \tag{A.17}$$

Constraint A.12 handles the requirement that each task is performed by maximum one vessel each shift. The CTVs and RHIBs start at the depot. Therefore, constraint A.13 makes sure the depot task is performed by each vessel during each shift. AVs can start from an offshore location at one of the wind farms. For this reason, constraint A.14 ensures that the start depot task is performed by an AV that is located at the depot and constraint A.15 ensures the same for the end depot task. In the model of Raknes et al. the nodes represent the wind farms and the tasks of the wind turbines in the farm are associated with the wind farm node. Constraint A.16 restricts that a task m at wind farm i can only be performed by CTV v if v is located at i during the shift. Constraint A.17 concerns this restriction for AVs.

$$x_{mvs} = x_{(m+|M^-|)vs}, \qquad m \in M^-, v \in V_m, s \in S \tag{A.18}$$

$$\sum_{v \in V^m} x_{mvs} = 0, \qquad m \in M^-, s \in S | R_{ms} = 0 \tag{A.19}$$

$$\sum_{m \in M^P} \sum_{v \in V_m} x_{mvs} \leq B, \qquad s \in S | K_{ms} = 0 \tag{A.20}$$

A delivery and pick-up task at the same turbine must be performed by the same vessel. This is ensured by constraint A.18. Constraint A.19 prohibits performing a task during a shift for which $R_{ms} = 0$, which means that the task is not ready to be performed in that shift. In the model there is a desired number of preventive maintenance tasks to be performed per shift in addition to the corrective maintenance tasks. Extra preventive maintenance tasks can be performed if there is time or capacity left during the shift. However, constraint A.20 makes sure that if the energy production is higher than a specified limit, the number of performed preventive tasks does not exceed the desired number of preventive tasks.

$$T_m^{MT} - \sum_{v \in V_m} \sum_{h=1}^{s} (t_{(m+|M^-|)vh} - t_{mvh} - T^{PD} x_{mvh}) + (T_s^{SHIFT} - T^{PD}) f_{ms} \geq \delta, \qquad m \in M^-, s \in S \tag{A.21}$$

$$\sum_{v \in V_m} \sum_{h=1}^{s} (t_{(m+|M^-|)vh} - t_{mvh} - T^{PD} x_{mvh}) \geq T_m^{MT} f_{ms} \qquad m \in M^-, s \in S \tag{A.22}$$

$$\sum_{v \in V_m} x_{mvs} \leq 1 - f_{m(s-1)}, \qquad m \in M^-, s \in S \setminus \{1\} \tag{A.23}$$

The constraints above (equation A.21 till A.23) handle the variables that indicate in which shifts each task is completed. f_{ms} becomes one by means of constraint A.21 if task m is completed within shift s. f_{ms} is forced to zero by constraint A.22 if task m is not completed within shift s. Constraint A.23 restricts that a task m is executed during shift s after the task is completed.

$$c_m \geq C_m^{NC*} (T_m^{MT} - \sum_{v \in V_m} \sum_{s \in S} (t_{(m+|M^-|)vs} - t_{mvs} - T^{PD} x_{mvs})), \qquad m \in M^C \cap M^- \tag{A.24}$$

$$c_m \geq C_m^{NP*} (T_m^{MT} - \sum_{v \in V_m} \sum_{s \in S} (t_{(m+|M^-|)vs} - t_{mvs} - T^{PD} x_{mvs})), \qquad m \in M^P \cap M^- \tag{A.25}$$

Constraints A.24 and A.25 determine the penalty costs for uncompleted tasks according to the remaining required time for the task, for corrective and preventive tasks respectively. Both constraints are based on the difference between task duration and the time between the drop-off and pick-up tasks minus the transfer time. The remaining task time is multiplied by a cost per time unit for that particular task.

Constraints for time management

$$t_{mvs} \leq T_s^{SHIFT} x_{mvs}, \qquad m \in M, v \in V_m, s \in S \tag{A.26}$$

$$t_{mvs} \geq L_{vs}^{W} \sum_{j \in N} y_{jivs} - T_s^{SHIFT} (1 - x_{mvs}), \qquad i \in N^W, m \in M_i^-, v \in V_m^C, s \in S \tag{A.27}$$

$$t_{mvs} \geq \sum_{j \in N} T_{jiv}^{T} y_{jivs} - T_s^{SHIFT} (1 - x_{mvs}), \qquad i \in N^W, m \in M_i^-, v \in V_m^C, s \in S \tag{A.28}$$

$$t_{mvs} \geq L_{vs}^{W} (\sum_{j \in N} y_{jivs} + w_{iv(s-1)}) - T_s^{SHIFT} (1 - x_{mvs}), \qquad i \in N^W, m \in M_i^-, v \in V_m^A, s \in S \tag{A.29}$$

$$t_{mvs} \geq T_{0iv}^{T} y_{0ivs} - T_s^{SHIFT} (1 - x_{mvs}), \qquad i \in N^W, m \in M_i^-, v \in V_m^A, s \in S \tag{A.30}$$

$$t_{mvs} + T^{PD} x_{mvs} \leq U_{vs}^{W}, \qquad m \in M^+, v \in V_m, s \in S \tag{A.31}$$

Constraint A.26 ensures that the start time of task m is set to zero if the task is not performed. The start time of drop-off tasks must be greater than or equal to both the lower bound of the weather window and the travel time to the wind farm. This is taken care of by constraint A.27 and A.28 respectively. For AVs, constraint A.29 ensures that start time of the drop-off tasks is great than of equal to the lower bound of the weather window. The start time of drop-off tasks performed by an AV must be greater than or equal to the travel time from the depot to the wind farm is the AV starts the shift at the depot (see constraint A.30). Constraint A.31 makes sure that pick-up tasks start in time in order to be able to transfer the technicians before the upper bound of the weather window.

$$t_{(m+|M^-|)vs} \geq t_{mvs} + T^{PD} x_{mvs}, \quad m \in M^-, v \in V_m, s \in S \tag{A.32}$$

$$t_{mvs} - t_{nvs} + \delta \leq T_s^{SHIFT}(1 - z_{mnvs}), \quad i \in N^W, m \in M_i^- \cup M_i^+, n \in M_i^- \cup M_i^+, v \in V_m \cap V_n, s \in S | m \neq n \tag{A.33}$$

$$t_{mvs} - t_{|M|vs} + T^{PD} x_{mvs} + T^T_{i|n|v} y_{i|N|vs} \leq T_s^{SHIFT}(1 - z_{m|M|vs}), \quad i \in N^W, m \in M_i^- \cup M_i^+, v \in V_m \cap V_n, s \in S \tag{A.34}$$

$$t_{mvs} - t_{nvs} + T^{PD} + T^T_{jiv} y_{jivs} \leq T_s^{SHIFT}(1 - z_{mnvs}), \quad i \in N^W, j \in N^W, m \in M_j^- \cup M_j^+, n \in M_i^- \cup M_i^+, v \in V_m \cap V_n, s \in S | m \neq n \tag{A.35}$$

The pick-up tasks should be performed after the drop-off task plus the transfer time. This is handled by constraint A.32. The time between the start times of consecutive tasks must be greater than or equal to the sum of the average travel time between turbines and the transfer time (see constraint A.33). Constraint A.34 ensures that the time between the start times of the end depot task and the previous task must be greater than the sum of the transfer time and the travel time between the last wind farm and the depot. The time between the start times of consecutive tasks that must be performed on different units should be greater than or equal to the travel time between the units and the transfer time. Therefore, constraint A.35 is added to the constraints for time management.

Constraints for the precedence of tasks

$$x_{mvs} = \sum_{n \in M \setminus \{0\}} z_{mnvs} \quad m \in M \setminus \{|M|\}, v \in V_m^C \cap V_n^C, s \in S \tag{A.36}$$

$$x_{mvs} = \sum_{n \in M \setminus \{|M|\}} z_{nmvs} \quad m \in M \setminus \{|0|\}, v \in V_m^C \cap V_n^C, s \in S \tag{A.37}$$

$$x_{mvs} = \sum_{n \in M \setminus \{0\}} z_{mnvs} \quad m \in M \setminus \{|M|\}, v \in V_m^R \cap V_n^R, s \in S \tag{A.38}$$

$$x_{mvs} = \sum_{n \in M \setminus \{|M|\}} z_{nmvs} \quad m \in M \setminus \{|0|\}, v \in V_m^R \cap V_n^R, s \in S \tag{A.39}$$

$$x_{mvs} \geq \sum_{n \in M \setminus \{0\}} z_{mnvs} \quad m \in M \setminus \{|M|\}, v \in V_m^A \cap V_n^A, s \in S \tag{A.40}$$

$$x_{mvs} \geq \sum_{n \in M \setminus \{|M|\}} z_{nmvs} \quad m \in M \setminus \{|0|\}, v \in V_m^A \cap V_n^A, s \in S \tag{A.41}$$

$$\sum_{m \in M \setminus \{|M|\}} \sum_{n \in M \setminus \{0\}} z_{mnvs} \geq \sum_{m \in M} x_{mvs} - 1, \quad v \in V_m^A \cap V_n^A, s \in S \tag{A.42}$$

$$t_{nvs} x_{mvs} \geq t_{(m+|N|)vs} x_{nvs}, \quad i, j \in N^W, m \in M_i, n \in M_j, v \in V_m \cap V_n, s \in S | i \neq j, E_m = 1 \tag{A.43}$$

$$z_{mnvs} \leq y_{jivs}, \quad m \in M_j^- \cup M_j^+, n \in M_i^- \cup M_i^+, i, j \in N, v \in V_m \cap V_n, s \in S | i \neq j \tag{A.44}$$

For the precedence of tasks performed by CTVs, constraints A.36 and A.37 make sure that each task has a previous and a following task except for the depot tasks. The same applies for RHIBs (see constraints A.38 and A.39). Constraints A.40 and A.41 ensure that the tasks performed by AVs have maximum one previous and following task except for the depot tasks. As an AV can stay offshore, the first or last maintenance tasks at wind farms do not have a previous or following task if the AV stayed or stays offshore. To make sure that the rest of the tasks do have a previous and following task constraint A.42 states that the number of consecutive tasks must be minimal as much as the number of performed tasks minus one. Constraint A.43 ensures that for tasks that require the vessel to stay, subsequent tasks at other turbines or solar units can be started after this task is finished. If consecutive tasks are performed at different turbines or solar units the vessel must travel between the units. Therefore constraint A.44 is added to the constraints of precedence.

Constraints for the downtime

$$l_{ms} \geq T^{DAY}(1 - f_{ms}), \qquad m \in M^C, s \in S \qquad \text{(A.45)}$$

$$l_{ms} \geq \sum_{v \in V_m} (t_{(m+|M^-|)vs} + T^{PD} x_{mvs}) - T_s^{SHIFT}(1 - (f_{ms} - f_{m(s-1)})), \qquad m \in M^C, s \in S \backslash \{1\} \qquad \text{(A.46)}$$

$$l_{ms} \geq \sum_{v \in V_m} (t_{(m+|M^-|)vs} + T^{PD} x_{mvs}) - T_s^{SHIFT}(1 - f_{ms}), \qquad m \in M^C, s = 1 \qquad \text{(A.47)}$$

For corrective tasks the downtime starts at the beginning of the planning period. If the task is not performed during a shift constraint A.45 forces the time counter of the downtime to be greater than or equal to the number of time units in one day. When a task is completed in a shift, constraint A.46 restricts the time counter to stop after the technicians are picked-up and transferred to the vessel. Constraints A.47 does the same but for the first shift of the planning period, as this shift has no preceding shift.

$$l_{ms} \geq \sum_{v \in V_m} (t_{(m+|M^-|)vs} + T^{PD} x_{mvs} - t_{mvs}), \qquad m \in M^P, s \in S, \qquad \text{(A.48)}$$

$$\sum_{v \in V_m} (t_{(m+|M^-|)vs} + T^{PD} x_{mvs} - t_{mvs}) \geq T^{MINt} x_{mvs}, \qquad m \in M^P, s \in S \qquad \text{(A.49)}$$

For preventive tasks the turbines are only shut down during the maintenance tasks. Constraint A.48 makes sure that the downtime is minimal as much as the time between the start of the drop-off task till the moment that the technicians are transferred back to the vessel. Constraint A.49 avoids that the technicians are left at the turbine for a time period that is so short that they in reality do not have time to perform any maintenance. This is avoided by means of a minimal time for preventive maintenance tasks.

Constraints for the balance of technicians:

$$p_{mvs} - P_n - p_{nvs} \leq (Q_v - P_n)(1 - z_{mnvs}), \qquad m \in M \backslash \{|M|\}, n \in M \backslash \{0\}, v \in V_m \cap V_n, s \in S \qquad \text{(A.50)}$$

$$p_{mvs} - P_n - p_{nvs} \geq (-P_n - Q_v)(1 - z_{mnvs}), \qquad m \in M \backslash \{|M|\}, n \in M \backslash \{0\}, v \in V_m \cap V_n, s \in S \qquad \text{(A.51)}$$

Constrained A.50 and A.51 are linearized constraints that ensure the balance of technicians for consecutive tasks m and n that are performed respectively. The constraints state that the number of technicians on the vessel directly after task n must be equal to the sum of the number of technicians directly after task m and the number of technicians required for task n.

$$p_{mvs} \leq (Q_v - P_m) x_{mvs}, \qquad m \in M^-, v \in V_m, s \in S \qquad \text{(A.52)}$$

$$p_{mvs} \leq Q_v x_{mvs}, \qquad m \in M^+, v \in V_m, s \in S \qquad \text{(A.53)}$$

$$p_{mvs} \geq -P_m x_{mvs}, \qquad m \in M^+, v \in V_m, s \in S \qquad \text{(A.54)}$$

$$p_{mvs} \leq Q_v x_{mvs}, \qquad m = \{0\} \cup m = \{|M|\}, v \in V_m, s \in S \qquad \text{(A.55)}$$

$$p_{mvs} \geq (Q_v - P_m) x_{mvs}, \qquad m \in M^-, v \in V_m, s \in S | E_m = 1 \qquad \text{(A.56)}$$

Constaints A.52 until A.56 make sure that the vessel capacity is never exceeded.

The domains of the decision variable

$$x_{mvs} \in [0,1], \quad m \in M, v \in V_m, s \in S \tag{A.57}$$
$$y_{ijvs} \in [0,1], \quad i,j \in N, v \in V, s \in S, i \neq j \tag{A.58}$$
$$z_{mnvs} \in [0,1], \quad i \in N^W, m,n \in M_i, v \in V_m \cap V_n, s \in S \tag{A.59}$$
$$w_{ivs} \in [0,1], \quad i \in N, v \in V^A, s \in S \tag{A.60}$$
$$f_{mvs} \in [0,1], \quad m \in M, v \in V_m, s \in S \tag{A.61}$$
$$t_{mvs} \geq 0, \quad m \in M, v \in V, s \in S \tag{A.62}$$
$$l_{ms} \geq 0, \quad m \in M, s \in S \tag{A.63}$$
$$p_{mvs} \geq 0, integer, \quad m \in M, v \in V_m, s \in S \tag{A.64}$$
$$c_m \geq 0, integer, \quad m \in M \tag{A.65}$$

Constraints A.57 until A.65 determine the domains of the decision variables.

B

Model verification

This appendix presents the details of the OWSF model verification. The results are presented in a table that gives an overview of the different shifts and the different vessels. The results are presented from the base scenario and the three verification scenarios.

B.1. Base scenario

The base scenario is described in chapter 5. It represents a imagined wind farm of only three wind turbines and one solar unit. For each wind turbine and solar unit a number of corrective and preventive tasks are appointed. Figure B.1 presents the sequence of the tasks per shift per vessel and figure B.2 presents the execution of each maintenance task.

Vessel	Shift 1 Task	Shift 1 Start time (h)	Shift 1 Technicians at vessel after task	Shift 2 Task	Shift 2 Start time (h)	Shift 2 Technicians at vessel after task	Shift 3 Task	Shift 3 Start time (h)	Shift 3 Technicians at vessel after task	Shift 4 Task	Shift 4 Start time (h)	Shift 4 Technicians at vessel after task
CTV 1	D-0	0.00	35	D-0	0.00	0	D-0	0.00	0	D-0	0.00	0
	NI-3	1.94	32	D-5	8.00	0	D-5	8.00	0	D-5	8.00	0
	NI-3	1.94	29									
	NI-1	2.46	26									
	EI-1	2.46	24									
	EI-1	2.46	22									
	EI-1+	5.94	24									
	EI-1+	5.94	26									
	NI-3+	6.44	29									
	NI-3+	6.44	32									
	NI-1+	6.96	35									
	D-5	8.00	35									
SOV 2	D-0	0.00	40	NR-3	0.00	35	NR-3	0.00	35	D-0	0.00	0
	NR-2	0.50	35	NR-3+	7.50	40	NR-3+	4.00	40			
	ER-2	0.50	32									
	EI-2	4.00	30									
	ER-2+	4.00	33									
	NR-2+	6.00	38									
	EI-2+	6.47	40									
CTV 3	D-0	0.00	0	D-0	0.00	0	D-0	0.00	0	D-0	0.00	0
	D-5	8.00	0	D-5	8.00	0	D-5	8.00	0	D-5	8.00	0
CTV 4	D-0	0.00	0	D-0	0.00	35	D-0	0.00	0	D-0	0.00	0
	D-5	8.00	0	EI-2	0.95	33	D-5	8.00	0	D-5	8.00	0
				EI-1	1.47	31						
				EI-1	1.47	29						
				EI-1+	6.98	31						
				EI-1+	6.98	33						
				EI-2+	7.48	35						
				D-5	8.00	35						
RHIB 5	D-0	0.00	6	D-0	0.00	6	D-0	0.00	6	D-0	0.00	6
	SR-4	1.00	4	D-5	8.00	6	D-5	8.00	6	D-5	8.00	6
	SI-4	2.00	2									
	SI-4+	3.50	4									
	SR-4+	3.50	6									
	SI-4	5.64	4									
	SI-4+	7.14	6									
	D-5	8.00	6									

Figure B.1: Results of the base scenario including the sequence of the executed tasks

Task	Shift	Start time (h)	End time (h)	Duration (h)	Required duration (h)	Time counter (h)	Finished
NI-1							
	1	2.46	6.96	4.50	4.00	5.00	1
EI-1							
	1	2.46	5.94	3.48	8.00	3.98	0
	2	1.47	6.98	5.52	8.00	6.02	1
EI-1							
	1	2.46	5.94	3.48	8.00	3.98	0
	2	1.47	6.98	5.52	8.00	6.02	1
ER-2							
	1	0.50	4.00	3.50	3.00	4.50	1
EI-2							
	1	4.00	6.47	2.47	8.00	2.97	0
	2	0.95	7.48	6.53	8.00	7.03	1
NR-2							
	1	0.50	6.00	5.50	5.00	6.50	1
NR-3							
	2	0.00	5.50	5.50	5.00	6.00	1
NI-3							
	1	1.94	6.44	4.50	4.00	5.00	1
NR-3							
	2	5.50	7.50	2.00	5.00	24.00	0
	3	0.00	4.00	4.00	5.00	4.50	1
NI-3							
	1	1.94	6.44	4.50	4.00	5.00	1
SI-4							
	1	5.64	7.14	1.50	1.00	2.00	1
SR-4							
	1	1.00	3.50	2.50	2.00	4.00	1
SI-4							
	1	2.00	3.50	1.50	1.00	2.00	1

Figure B.2: Results of the base scenario including the completion of the tasks

B.2. Scenario 1

Scenario 1 contains different weather conditions per shift. Shift 1 and 2 have high wind speed and low solar radiation. In the input that results in small weather windows, no extra preventive tasks can be performed at the wind turbines, the downtime costs for wind turbines is high, and the downtime costs for the solar units is low. Shift 3 and 4 are windless and have high solar radiation. This means that weather windows for shift 3 and 4 are equal to the shift duration, no extra preventive maintenance tasks can be performed at the solar units, the downtime cost for the wind turbines is low, and the downtime cost for the solar units is high. Figure B.3 presents the sequence of the tasks per shift per vessel and figure B.4 presents the execution of each maintenance task.

	Shift 1			Shift 2			Shift 3			Shift 4		
Vessel	Task	Start time (h)	Technicians at vessel after task	Task	Start time (h)	Technicians at vessel after task	Task	Start time (h)	Technicians at vessel after task	Task	Start time (h)	Technicians at vessel after task
CTV 1	D-0	0	2	D-0	0	0	D-0	0	0	D-0	0	0
	EI-1	2.43	0	D-5	8	0	D-5	8	0	D-5	8	0
	EI-1+	4.48	2									
	D-5	8	2									
SOV 2	D-0	0	40	NR-3	0	35	NR-2	0	35	NR-3	0	35
	NR-3	0.5	35	NI-3	0	32	EI-2	0	33	NR-3+	4	40
	NR-3+	4	40	NR-3+	4.5	37	NR-2+	5.5	38			
	NR-3	4	35	NI-3+	4.5	40	EI-2+	7.5	40			
	NR-3+	4.5	40									
CTV 3	D-0	0	0	D-0	0	0	D-0	0	10	D-0	0	0
	D-5	8	0	D-5	8	0	EI-1	0.54	8	D-5	8	0
							EI-1	0.54	6			
							NI-1	0.54	3			
							NI-3	2.48	0			
							NI-1+	5.04	3			
							NI-3+	6.98	6			
							EI-1+	7.48	8			
							EI-1+	7.48	10			
							D-5	8	10			
CTV 4	D-0	0	5	D-0	0	2	D-0	0	0	D-0	0	0
	ER-2	0.54	2	EI-2	2.84	0	D-5	8	0	D-5	8	0
	EI-1	1.06	0	EI-2+	4.34	2						
	EI-1+	3.11	2	D-5	8	2						
	ER-2+	4.04	5									
	D-5	8	5									
RHIB 5	D-0	0	6	D-0	0	0	D-0	0	0	D-0	0	0
	SR-4	1	4	D-5	8	0	D-5	8	0	D-5	8	0
	SI-4	1	2									
	SI-4+	2.5	4									
	SI-4	2.5	2									
	SR-4+	3.5	4									
	SI-4+	4	6									
	D-5	8	6									

Figure B.3: Results of scenario 1 including the sequence of the executed tasks

Task	Shift	Start time (h)	End time (h)	Duration (h)	Required duration (h)	Time counter (h)	Finished
NI-1							
	3	0.54	5.04	4.50	4.00	5.00	1
EI-1							
	1	2.43	4.48	2.06	8.00	2.56	0
	3	0.54	7.48	6.94	8.00	7.44	1
EI-1							
	1	1.06	3.11	2.06	8.00	2.56	0
	3	0.54	7.48	6.94	8.00	7.44	1
ER-2							
	1	0.54	4.04	3.50	3.00	4.54	1
EI-2							
	2	2.84	4.34	1.50	8.00	2.00	0
	3	0.00	7.50	7.50	8.00	8.00	1
NR-2							
	3	0.00	5.50	5.50	5.00	6.00	1
NR-3							
	1	0.50	4.00	3.50	5.00	24.00	0
	2	0.00	2.50	2.50	5.00	3.00	1
NI-3							
	3	2.48	6.98	4.50	4.00	5.00	1
NR-3							
	1	4.00	4.50	0.50	5.00	24.00	0
	2	2.50	4.50	2.00	5.00	24.00	0
	4	0.00	4.00	4.00	5.00	4.50	1
NI-3							
	2	0.00	4.50	4.50	4.00	5.00	1
SI-4							
	1	2.50	4.00	1.50	1.00	2.00	1
SR-4							
	1	1.00	3.50	2.50	2.00	4.00	1
SI-4							
	1	1.00	2.50	1.50	1.00	2.00	1

Figure B.4: Results of scenario 1 including the completion of the tasks

B.3. Scenario 2

Scenario 2 contains the very expensive use of an RHIB. The cost of using an RHIB is at least 10 time higher than the use of the other vessels. Figure B.5 presents the sequence of the tasks per shift per vessel and figure B.6 presents the execution of each maintenance task.

	Shift 1			Shift 2			Shift 3			Shift 4		
Vessel	Task	Start time (h)	Technicians at vessel after task	Task	Start time (h)	Technicians at vessel after task	Task	Start time (h)	Technicians at vessel after task	Task	Start time (h)	Technicians at vessel after task
CTV 1	D-0	0.00	35	D-0	0.00	6	D-0	0.00	35	D-0	0.00	35
	NI-1	0.54	32	EI-1	0.54	4	D-5	8.00	35	D-5	8.00	35
	EI-1	1.58	30	EI-1	0.54	2						
	NI-3	2.10	27	EI-2	1.06	0						
	NI-3	2.10	24	EI-2+	4.56	2						
	NI-1+	5.04	27	EI-1+	5.06	4						
	EI-1	5.04	25	EI-1+	7.48	6						
	EI-1+	6.07	27	D-5	8.00	6						
	NI-3+	6.60	30									
	NI-3+	6.60	33									
	EI-1+	7.10	35									
	D-5	8.00	35									
SOV 2	D-0	0.00	40	NR-3	0.00	35	NR-3	0.00	35	D-0	0.00	0
	NR-2	0.50	35	NR-3+	5.50	40	NR-3+	4.00	40			
	EI-2	0.50	33	NR-3	5.50	35						
	ER-2	0.50	30	NR-3+	7.50	40						
	ER-2+	4.00	33									
	EI-2+	6.00	35									
	NR-2+	6.00	40									
CTV 3	D-0	0.00	0	D-0	0.00	0	D-0	0.00	35	D-0	0.00	35
	D-5	8.00	0	D-5	8.00	0	D-5	8.00	35	D-5	8.00	35
CTV 4	D-0	0.00	35	D-0	0.00	0	D-0	0.00	35	D-0	0.00	35
	SR-4	0.54	33	D-5	8.00	0	D-5	8.00	35	D-5	8.00	35
	SR-4+	3.04	35									
	SI-4	3.04	33									
	SI-4+	4.54	35									
	SI-4	5.46	33									
	SI-4+	6.96	35									
	D-5	8.00	35									
RHIB 5	D-0	0.00	6	D-0	0.00	6	D-0	0.00	6	D-0	0.00	35
	D-5	8.00	6	D-5	8.00	6	D-5	8.00	6	D-5	8.00	35

Figure B.5: Results of scenario 2 including the sequence of the executed tasks

Task	Shift	Start time (h)	End time (h)	Duration (h)	Required duration (h)	Time counter (h)	Finished
NI-1							
	1	0.54	5.04	4.50	4.00	5.00	1
EI-1							
	1	1.58	6.07	4.48	8.00	4.98	0
	2	0.54	5.06	4.52	8.00	5.02	1
EI-1							
	1	5.04	7.10	2.06	8.00	2.56	0
	2	0.54	7.48	6.94	8.00	7.44	1
ER-2							
	1	0.50	4.00	3.50	3.00	4.50	1
EI-2							
	1	0.50	6.00	5.50	8.00	6.00	0
	2	1.06	4.56	3.50	8.00	4.00	1
NR-2							
	1	0.50	6.00	5.50	5.00	6.50	1
NR-3							
	2	0.00	5.50	5.50	5.00	6.00	1
NI-3							
	1	2.10	6.60	4.50	4.00	5.00	1
NR-3							
	2	5.50	7.50	2.00	5.00	24.00	0
	3	0.00	4.00	4.00	5.00	4.50	1
NI-3							
	1	2.10	6.60	4.50	4.00	5.00	1
SI-4							
	1	3.04	4.54	1.50	1.00	2.00	1
SR-4							
	1	0.54	3.04	2.50	2.00	3.54	1
SI-4							
	1	5.46	6.96	1.50	1.00	2.00	1

Figure B.6: Results of scenario 2 including the completion of the tasks

B.4. Scenario 3

Scenario 3 contains A very high cost of an SOV staying offshore. The cost of an SOV staying offshore in between shifts is 10 times higher than in the base scenario. Figure B.7 presents the sequence of the tasks per shift per vessel and figure B.7 presents the execution of each maintenance task.

Vessel	Shift 1			Shift 2			Shift 3			Shift 4		
	Task	Start time (h)	Technicians at vessel after task	Task	Start time (h)	Technicians at vessel after task	Task	Start time (h)	Technicians at vessel after task	Task	Start time (h)	Technicians at vessel after task
CTV 1	D-0	0.00	4	D-0	0.00	4	D-0	0.00	0	D-0	0.00	0
	EI-2	1.31	2	EI-1	0.60	2	D-5	8.00	0	D-5	8.00	0
	SI-4	4.17	0	EI-1	0.64	0						
	SI-4+	5.67	2	EI-1+	2.78	2						
	EI-2+	6.17	4	EI-1+	7.43	4						
	D-5	8.00	4	D-5	8.00	4						
SOV 2	D-0	0.00	40	NR-2	0.00	35	NR-3	0.00	35	D-0	0.00	0
	NR-3	0.50	35	EI-2	1.36	33	NR-3+	4.50	40			
	NI-3	1.50	32	NR-2+	5.50	38						
	NI-3	1.50	29	EI-2+	5.50	40						
	NR-3+	6.00	34									
	NI-3+	6.00	37									
	NI-3+	6.00	40									
	NR-3	6.00	35									
	NR-3+	7.50	40									
CTV 3	D-0	0.00	2	D-0	0.00	0	D-0	0.00	0	D-0	0.00	0
	SI-4	0.54	0	D-5	8.00	0	D-5	8.00	0	D-5	8.00	0
	SI-4+	2.04	2									
	D-5	8.00	2									
CTV 4	D-0	0.00	8	D-0	0.00	0	D-0	0.00	0	D-0	0.00	0
	EI-1	0.54	6	D-5	8.00	0	D-5	8.00	0	D-5	8.00	0
	NI-1	0.54	3									
	ER-2	1.06	0									
	ER-2+	4.56	3									
	NI-1+	5.06	6									
	EI-1	5.09	4									
	EI-1+	7.31	6									
	EI-1+	7.35	8									
	D-5	8.00	8									
RHIB 5	D-0	0.00	6	D-0	0.00	0	D-0	0.00	0	D-0	0.00	0
	SR-4	1.00	4	D-5	8.00	0	D-5	8.00	0	D-5	0.00	0
	SR-4+	3.50	6									
	D-5	8.00	6									

Figure B.7: Results of scenario 3 including the sequence of the executed tasks

Task	Shift	Start time (h)	End time (h)	Duration (h)	Required duration (h)	Time counter (h)	Finished
NI-1							
	1	1.50	6.00	4.50	4.00	5.00	1
EI-1							
	1	1.09	6.38	5.30	8.00	5.80	0
	2	3.20	6.90	3.70	8.00	4.20	1
EI-1							
	1	1.17	6.41	5.25	8.00	5.75	0
	2	3.17	6.92	3.75	8.00	4.25	1
ER-2							
	1	0.54	4.04	3.50	3.00	4.54	1
EI-2							
	1	0.55	7.48	6.93	8.00	7.43	0
	2	0.56	2.63	2.07	8.00	2.57	1
NR-2							
NR-3							
NI-3							
	1	2.46	6.96	4.50	4.00	5.00	1
NR-3							
NI-3							
	1	2.46	6.96	4.50	4.00	5.00	1
SI-4							
	1	4.25	5.75	1.50	1.00	2.00	1
SR-4							
	1	1.00	3.50	2.50	2.00	4.00	1
SI-4							
	1	4.25	5.75	1.50	1.00	2.00	1

Figure B.8: Results of scenario 3 including the completion of the tasks

C

Case study input

C.1. Power curve

For the estimation of the power loss during maintenance or after failure while waiting for the maintenance the power curve is required. The power loss is determined with the weather data and the power curve. As the ECN report [90] does not provide a continuous power curve, a fitted polynomial is required. The power curve data from the ECN report is implemented in python. The function numpy.polyfit is used to find a fitted polynomial. This function requires the input of which degree polynomial. Figure C.1 shows the different results for different degrees of polynomials.

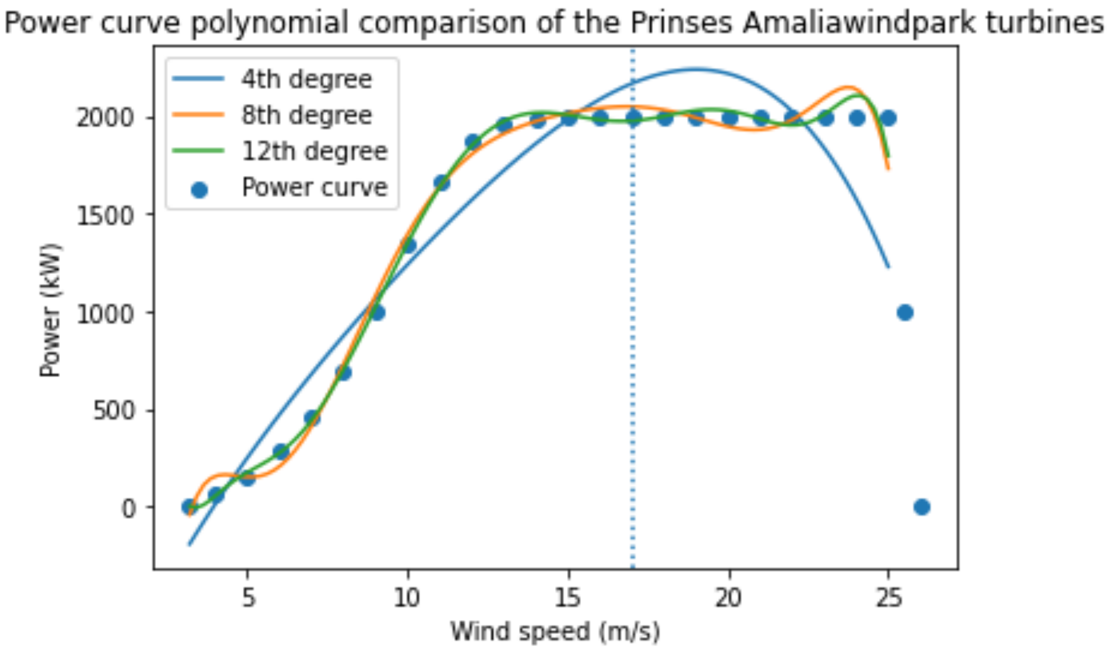

Figure C.1: Polynomial comparison for the power curve of the Prinses Amailiawindpark turbines

In figure C.1 can be seen that the 8th and 12th degree polynomial come very close to the power curve points. Therefore, a analysis of the Means Square Error (MSE) is applied. Figure C.2 shows that the 9th degree polynomial fits the provided power curve the best.

Degree	MSE
8	2664.32
9	130.72
10	132.83
11	145.88
12	329.19

Figure C.2: MSE analysis of polynomial

D
Validation results

Chapter 7 provides a discussion and validation of the results of the case study. This appendix contains additional information to support the validation.

D.1. Weather dependency

In order to show the dependency of the case study results to weather conditions, both scenarios are analysed with extended time windows. So in these validation scenarios all vessels can sail during all shifts. The results are presented in figure D.1 and D.2. In the results the maintenance is indeed performed in shift 1 and 2.

	Task	Start time (h)	Technicians at vessel after task	Task	Start time (h)	Technicians at vessel after task
	Shift 1			Shift 2		
CTV 1	Start at depot	0.00	12	Start at depot	0.00	0
	Control and protection system turbine-5	0.64	9	End at depot	8.00	0
	Blade adjustment-4	0.95	6			
	Transformer 1-2	1.26	3			
	Control and protection system turbine-5+	4.89	6			
	Blade adjustment-4+	5.20	9			
	Transformer 1-2+	7.75	12			
	End at depot	8.00	12			
CTV 2	Start at depot	0.00	0	Start at depot	0.00	0
	End at depot	8.00	0	End at depot	8.00	0
CTV 3	Start at depot	0.00	0	Start at depot	0.00	12
	End at depot	8.00	0	Transformer 1-2	0.67	9
				Transformer 1-2+	2.68	12
				End at depot	8.00	12
SOV 4	Start at depot	0.00	0	Start at depot	0.00	0
	End at depot	8.00	0	End at depot	8.00	0
RHIB 5	Start at depot	0.00	4	Start at depot	0.00	4
	Mooring system lines solar-7	0.45	1	Mooring system lines solar-7	0.45	1
	Mooring system lines solar-7+	6.11	4	Mooring system lines solar-7+	7.30	4
	End at depot	8.00	4	End at depot	8.00	4
	Shift 3					
CTV 1	Start at depot	0.00	12	Start at depot	0.00	0
	End at depot	8.00	12	End at depot	8.00	0
CTV 2	Start at depot	0.00	12	Start at depot	0.00	0
	End at depot	8.00	12	End at depot	8.00	0
CTV 3	Start at depot	0.00	12	Start at depot	0.00	0
	End at depot	8.00	12	End at depot	8.00	0
SOV 4	Start at depot	0.00	0	Start at depot	0.00	0
	End at depot	8.00	0	End at depot	8.00	0
RHIB 5	Start at depot	0.00	4	Start at depot	0.00	4
	End at depot	8.00	4	End at depot	8.00	4

Figure D.1: February scenario result without weather constraints

	Task	Start time (h)	Technicians at vessel after task	Task	Start time (h)	Technicians at vessel after task
	Shift 1			Shift 2		
CTV 1	Start at depot	0.00	12	Start at depot	0.00	9
	Wind Turbine Regular Maintenance-2	0.67	9	Wind Turbine Regular Maintenance-3	0.71	6
	Wind Turbine Regular Maintenance-1	0.98	6	Wind Turbine Regular Maintenance-1	1.53	3
	Wind Turbine Regular Maintenance-3	1.26	3	Wind Turbine Regular Maintenance-2	2.38	0
	Wind Turbine Regular Maintenance-3+	7.25	6	Wind Turbine Regular Maintenance-2+	6.13	3
	Wind Turbine Regular Maintenance-1+	7.50	9	Wind Turbine Regular Maintenance-1+	6.97	6
	Wind Turbine Regular Maintenance-2+	7.75	12	Wind Turbine Regular Maintenance-3+	7.74	9
	End at depot	8.00	12	End at depot	8.00	9
CTV 2	Start at depot	0.00	0	Start at depot	0.00	0
	End at depot	0.00	0	End at depot	0.00	0
CTV 3	Start at depot	0.00	0	Start at depot	0.00	0
	End at depot	0.00	0	End at depot	0.00	0
SOV 4	Start at depot	0.00	0	Start at depot	0.00	0
	End at depot	0.00	0	End at depot	0.00	0
RHIB 5	Start at depot	0.00	4	Start at depot	0.00	4
	Mooring system chains solar-8	0.43	1	Mooring system chains solar-8	0.43	1
	Mooring system chains solar-8+	7.32	4	Mooring system chains solar-8+	7.32	4
	End at depot	8.00	4	End at depot	8.00	4
	Shift 3			Shift 4		
CTV 1	Start at depot	0.00	12	Start at depot	0.00	9
	Wind Turbine Regular Maintenance-2	0.67	9	Wind Turbine Regular Maintenance-2	0.67	6
	Wind Turbine Regular Maintenance-1	0.98	6	Wind Turbine Regular Maintenance-1	0.98	3
	Wind Turbine Regular Maintenance-3	1.26	3	Wind Turbine Regular Maintenance-3	1.26	0
	Wind Turbine Regular Maintenance-3+	7.25	6	Wind Turbine Regular Maintenance-3+	7.25	3
	Wind Turbine Regular Maintenance-1+	7.50	9	Wind Turbine Regular Maintenance-1+	7.50	6
	Wind Turbine Regular Maintenance-2+	7.75	12	Wind Turbine Regular Maintenance-2+	7.75	9
	End at depot	8.00	12	End at depot	8.00	9
CTV 2	Start at depot	0.00	0	Start at depot	0.00	0
	End at depot	0.00	0	End at depot	0.00	0
CTV 3	Start at depot	0.00	0	Start at depot	0.00	0
	End at depot	0.00	0	End at depot	0.00	0
SOV 4	Start at depot	0.00	0	Start at depot	0.00	0
	End at depot	0.00	0	End at depot	0.00	0
RHIB 5	Start at depot	0.00	4	Start at depot	0.00	4
	End at depot	0.00	4	End at depot	0.00	4

Figure D.2: May scenario result without weather constraints

D.2. Vessel cost and speed dependency

In section 7.2 the dependency of the case study results on vessel price and speed is analysed. The section describes a tipping point for whether an RHIB is included in the optimal route and schedule related to RHIB cost and speed. Figure D.3 and D.4 show the results for when the RHIB is not included. Figure D.3 shows the results for when the cost of an RHIB is 434 euro and figure D.4 shows the results for when the speed of an RHIB is 16 km/h.

	Task	Start time (h)	Technicians at vessel after task	Task	Start time (h)	Technicians at vessel after task
	Shift 1			Shift 2		
CTV 1	Start at depot	0.00	0	Start at depot	0.00	0
	End at depot	8.00	0	End at depot	8.00	0
CTV 2	Start at depot	0.00	0	Start at depot	0.00	0
	End at depot	8.00	0	End at depot	8.00	0
CTV 3	Start at depot	0.00	0	Start at depot	0.00	0
	End at depot	8.00	0	End at depot	8.00	0
SOV 4	Start at depot	0.00	0	Start at depot	0.00	0
	End at depot	8.00	0	End at depot	8.00	0
RHIB 5	Start at depot	0.00	0	Start at depot	0.00	0
	End at depot	8.00	0	End at depot	8.00	0
	Shift 3			Shift 4		
CTV 1	Start at depot	0.00	12	Start at depot	0.00	12
	Mooring system lines solar-7	0.68	9	End at depot	8.00	12
	Mooring system lines solar-7+	7.07	12			
	End at depot	8.00	12			
CTV 2	Start at depot	0.00	0	Start at depot	0.00	12
	End at depot	8.00	0	Mooring system lines solar-7	0.68	9
				Mooring system lines solar-7+	6.80	12
				End at depot	8.00	12
CTV 3	Start at depot	0.00	9	Start at depot	0.00	3
	Transformer 1-2	0.67	6	Transformer 1-2	0.67	0
	Blade adjustment-4	0.98	3	Transformer 1-2+	2.09	3
	Control and protection system turbine-5	1.29	0	End at depot	8.00	3
	Blade adjustment-4+	5.23	3			
	Control and protection system turbine-5+	5.54	6			
	Transformer 1-2+	7.75	9			
	End at depot	8.00	9			
SOV 4	Start at depot	0.00	0	Start at depot	0.00	0
	End at depot	8.00	0	End at depot	8.00	0
RHIB 5	Start at depot	0.00	4	Start at depot	0.00	4
	End at depot	8.00	4	End at depot	8.00	4

Figure D.3: February scenario result after cost tipping point

The cost results of the base February scenario and of both variants after the tipping point are presented in figure D.5.

	Task	Start time (h)	Technicians at vessel after task	Task	Start time (h)	Technicians at vessel after task
	Shift 1			Shift 2		
CTV 1	Start at depot	0.00	0	Start at depot	0.00	0
	End at depot	8.00	0	End at depot	8.00	0
CTV 2	Start at depot	0.00	0	Start at depot	0.00	0
	End at depot	8.00	0	End at depot	8.00	0
CTV 3	Start at depot	0.00	0	Start at depot	0.00	0
	End at depot	8.00	0	End at depot	8.00	0
SOV 4	Start at depot	0.00	0	Start at depot	0.00	0
	End at depot	8.00	0	End at depot	8.00	0
RHIB 5	Start at depot	0.00	0	Start at depot	0.00	0
	End at depot	8.00	0	End at depot	8.00	0
	Shift 3			Shift 4		
CTV 1	Start at depot	0.00	12	Start at depot	0.00	0
	End at depot	8.00	12	Mooring system lines solar-7	0.68	9
				Mooring system lines solar-7+	7.07	12
				End at depot	8.00	12
CTV 2	Start at depot	0.00	9	Start at depot	0.00	3
	Transformer 1-2	0.67	6	Transformer 1-2	0.67	0
	Blade adjustment-4	0.98	3	Transformer 1-2+	2.09	3
	Control and protection system turbine-5	1.29	0	End at depot	8.00	3
	Blade adjustment-4+	5.23	3			
	Control and protection system turbine-5+	5.54	6			
	Transformer 1-2+	7.75	9			
	End at depot	8.00	9			
CTV 3	Start at depot	0.00	12	Start at depot	0.00	12
	Mooring system lines solar-7	0.68	9	End at depot	8.00	12
	Mooring system lines solar-7+	6.80	12			
	End at depot	8.00	12			
SOV 4	Start at depot	0.00	0	Start at depot	0.00	0
	End at depot	8.00	0	End at depot	8.00	0
RHIB 5	Start at depot	0.00	4	Start at depot	0.00	4
	End at depot	8.00	4	End at depot	8.00	4

Figure D.4: February scenario result after speed tipping point

	February	February after cost tipping point	February after speed tipping point
Travel cost	€ 1,018.63	€ 1,576.52	€ 1,576.52
Downtime cost	€ 19,125.65	€ 19,125.65	€ 19,125.65
Total cost	€ 20,144.28	€ 20,702.17	€ 20,702.17

Figure D.5: Cost results of the vessel cost speed ratio analysis