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Service Operation Vessels Fleet Size and Mix Location Routing for the Maintenance of an Offshore Floating Wind Farm

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Abstract: Mixed-integer linear programming is adopted to translate the routing of service operation vessels that support the logistic aspects of the maintenance of offshore floating wind farms into mathematical language. The models attempt to help the decision-makers by providing quantified tools to screen out the optimal planning for preventive maintenance. The models search for the optimal offshore base location, vessel's routing per day, vessel's capacity, and vessel fleet composition that minimize the total fixed and variable infrastructure cost. The integration of the vehicle fleet size and mix problem, facility location–allocation problem, and vehicle-routing problem with time window advances the state of the art. A realistic case study is shown, and the results and discussions demonstrated that the practical insights of the solutions, as well as the identification of the route patterns through a navigation route table, may improve the decision planning of preventive maintenance.

Keywords: floating wind turbines; preventive maintenance; operations and maintenance activities; fleet size and mix location vehicle-routing problem; mixed-integer linear programming

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1. Introduction

The energy generated by wind power has recently become one of the pillars to change the climate panorama presented nowadays due to it being generated by a clear and renewable source. In the search for locations that can reach a higher and more constant speed, the wind farm locations are changing from onshore to offshore, which increases the complexity of the maintenance planning. The wind conditions improve the unit time production but, also affect the maintenance planning because it may not be safe to perform maintenance under severe wind conditions [1]. Another example is the adoption of vessels to support operations and maintenance activities (O&M). The vessels are responsible for transferring technicians and delivering spare parts required to perform maintenance tasks. Different aspects of the maintenance strategies have been inducing the need for quantitative decision support models through the years, aiming at improving the planning process of the vessel's activities most efficiently and expeditiously [2].

The vehicle routing problem (VRP) is a well-studied topic applied in the logistic transportation sector. However, the variety of extensions and variations of the VRP arising in the offshore wind industry is a recent research topic. One of the significant studies that address the vehicle-routing and scheduling problem (VRSP) is presented by [3], which consists of defining a set of routes and scheduling the tasks to be accomplished by the vessels. The work presents arc-flow and path-flow formulations and a heuristic algorithm. Heuristic algorithms that have the similarity of extending the VRSP to include the heterogeneous fleet, multi-period time, multi-base locations, and multi-windfarms were developed by [4,5]. The main difference is that the heuristic presented by [4] also integrates the uncertainty of the weather conditions. The vehicle-scheduling problem (VSP) is another variation of the VRP. A mixed-integer linear programming (MILP) model is developed by [6], where the operational tasks are scheduled for a set of weather and breakdown scenarios.

The problem of searching for the minimum cost of a fleet of vessels and infrastructures to execute all the maintenance operations during the planning horizon is called the vehicle fleet size and mix problem (FSMP). Due to the uncertain nature of the chartering vessels during an established period, a stochastic programming model is an efficient approach adopted in the literature to solve the respective problem. This optimization technique is adopted by [7–9] to handle the uncertainties in economic aspects, operational process, demand, weather conditions and failure occurrence, respectively. Moreover, the pioneering work that studied the aspects of one VFSMP variation is [10], named fleet size and mix scheduling problem (FMSSP), in the offshore wind industry. The problem consists of defining the number of vessels necessary to accomplish the maintenance tasks and the respective scheduling plan for each vessel.

From the research work presented above, it can be noted that there is no restriction in the models regarding the travel time of the vessels to perform the routing and/or scheduling tasks. It is possible to argue that the studies are related to offshore wind farms located near shore (coastal), in shallow waters. But, nowadays, the wind industry is looking for sea locations that are not restricted by other sea activities or present even higher and constant wind speeds [11]. These locations are increasing the complexity of the wind farm system, as well as impacting the type of offshore wind turbine structure, changing the bottom-fixed turbines to floating offshore turbines. Accordingly, the distance from shore brings another limitation, that is, the vessel's travel time, which increases the logistic cost. New logistic strategies are being developed aiming at minimizing both time and cost. One idea is to establish an offshore base to supply the spare parts and accommodate the technicians.

The recent research works of [12,13] developed optimization models to study the optimal location-routing of the vessels (LRP). The location-routing problem consists of determining the optimal placement for one or more facilities and searching for the minimum facility cost and transportation. Both studies considered the service operation vessels (SOV) as the offshore base and the safe transfer boat (STB) as the daughter vessels to be used to transfer the technicians and spare parts. But the STB presents a smaller load capacity to carry out the supplies and a lower threshold for wind speed and wave height. The adoption and the crew transfer vessels (CTV) as daughter vessels of the SOV to increase the on-time and on-demand services is studied by [14]. The proposed model allows both vessels (SOV and CTV) to perform routes separately or combined. Nonetheless, the work does not determine the standby location of the SOV. Thus, none of the works in the presented in the literature described determines the necessary number of vessels to accomplish the new logistic.

The present paper adopts the CTV as the daughter's vessel, to perform the routes, and the SOV as the offshore base, having required technicians and spare parts during the planning horizon and provides mathematical decision models that integrate three main aspects of the logistic transportation sector: the location of the deposit, the fleet size of vehicles, and the respective routes for each vehicle. The main contributions of the present paper are:

1. The integration of the vehicle fleet size and mix problem, facility location-allocation problem and vehicle routing problem with time window searching for the optimal offshore floating wind activities planning.
2. The development of two mathematical models as rapid quantified screening tools to support the decision-makers to look for different aspects of an offshore floating wind farm.

2. Materials and Methods

2.1. Problem Description

The expansion of wind farms to deep waters and transitioning the offshore turbines to float concepts have been presenting a greater impact on the overall maintenance cost due to the unpredictable weather of the remote locations, higher failure occurrence because of the harsh marine environment, and extra inventory expenses to guarantee the transportation of spare parts and technicians in larger distances [15]. Besides the wind farm attributes, as well as the total number of turbines and their respective locations during a specific period, the O&M section prepares a list of turbines requiring maintenance. The different type of vessels presents different capacity for transferring technicians, load capacity to carry out the spare parts, sailing speed, the threshold for wind speed and wave height, which impacts the type of maintenance tasks each vessel can perform. Thus, the vessels are associated with a specific supply depot. The offshore wind farm distance from the onshore supply depot affects the navigation time. Attempting to increase the time that the vessels can be used, the supply base can be located offshore. In the case of an offshore base, the vessels can act as a servicing station having required technicians and daughter crafts. The vessels' voyage to supply the offshore wind farms needs to fit on the technicians' work shift performing a round trip visit to the offshore wind farm and their base. Figure 1 presents the comparison between the onshore and offshore supply base and the routing illustration. Therefore, the main decisions to be made are:

1. Where are the optimal locations of the offshore bases aiming at minimizing the logistic infrastructure and transportation costs?
2. How many of each type of vessel is necessary to attend the offshore wind farm?
3. What are the optimal routes for each vessel to deliver and pick up technicians and/or spare parts required to perform the maintenance tasks at each turbine during the planning horizon?

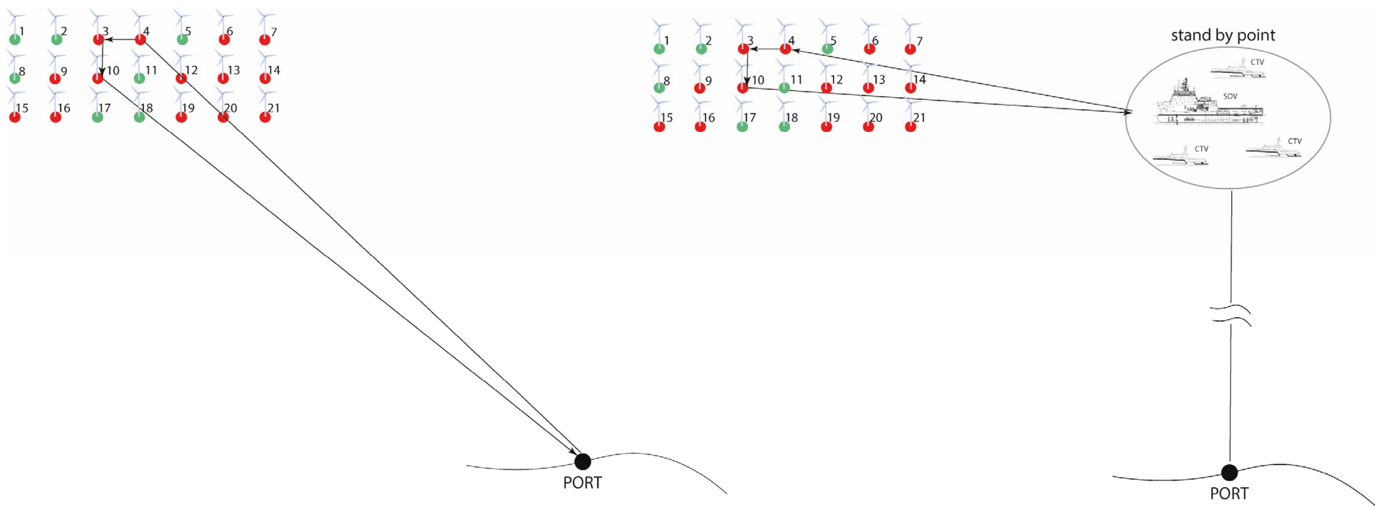

Figure 1. Onshore or offshore supply base location and the routing illustration. The red dots represent the turbines that are stopped waiting for maintenance.

2.2. Operation and Maintenance Activities

All the necessary efforts to maintain the daily operations of an offshore wind farm, including regular and irregular repairs, are part of the operation and maintenance activities [16]. A classification of the offshore floating wind turbine in modules is presented by [17] aiming at the identification of the failures of floating offshore wind turbines and their main components. Besides the reliability-centred maintenance approach, increasing attention is paid to condition-based maintenance (CBM) [18,19]. The framework based the maintenance on the health features of crucial wind turbine components, as determined by their failure rates [20]. A typical policy of the CBM is to perform maintenance when the pre-specified control limits of the degradation are reached.

The identification of the criticality of the components allows preventive measures to avoid the occurrence of failure and suggest corrective actions. The preventive and corrective maintenance tasks are two different activities to be performed at the wind turbine. The main characteristics of preventive maintenance (PM) are:

1. The PM is done every year for all the turbines.
2. The technicians need to spend a work shift per day per turbine.

3. A small crew is needed for one turbine maintenance.
4. Only crew transportation is needed, meaning that there is no requirement for the vessels to stay near the turbine.
5. PM is scheduled during the period with good weather conditions. It is based on statistical indicators that forecast when would be the most likely time window for PM.

If the weather is not favourable, it can be postponed but should be performed. Thus, the main characteristics of corrective maintenance (CM) are:

1. The CM need to be performed when the failures occur, attempting to reduce the downtime of the turbines.
2. Due to the first assumption, it can be performed during the whole year, which can suffer more impact by the weather conditions.
3. For each type of component failure, there is an associated mean time to repair, the specific number of technicians, and the vessel requirement to stay near the turbines.
4. Different types of vessels can perform different maintenance tasks (technicians transport and/or spare parts transport).

Due to the complexity, dynamic and uncertain nature of corrective maintenance, the present work considers only preventive maintenance logistics.

2.3. Assumptions and Concept Models

The functional description of the main system components allows the presentation and identification of the logistic network to be studied in more detail. The paper examines the preventive maintenance activities planning where the wind farm base is located offshore. The main logistic components of moving technicians to perform minor repairs are offshore turbine, technicians' demand, facilities (Port, SOV), vessels (CTV), and routes. The main function and the explicit assumptions of the system components are summarized as follows.

The offshore wind turbine is, basically, an assembly of components able to transform the wind force into electricity that is transferred to the offshore and onshore substations by cables. The size of the offshore turbine located at the same wind farm is similar and directly dependent on the amount of electricity production. This characteristic mutually interacts with the number of technicians to repair the turbines.

1. The size and capacity of electricity generation are beyond the scope of the paper.
2. The estimated number of turbines and their respective locations (represented as coordinates points in the x–y axis) are pre-defined data.
3. The number of technicians to perform the preventive maintenance repair in each turbine is pre-defined data.

The facilities of the system are the port and SOV. The port is an onshore supply base able to support the operation, manufacturing, and construction of an offshore wind farm and can house the vessels and handle the turbine components and technicians. As described above, the service operations vessel (SOV) is adopted in the present work not only as a supply vehicle used to transport materials and technicians to the offshore wind farm location but also to stay positioned at sea for at least one week, accommodating the technicians and serving as a warehouse to store the necessary spare part during the week planning horizon.

4. The facilities (Port, SOV, CTV) capacities are standardized and cannot be exceeded.

The crew transportation vessel (CTV) is adopted to transfer the technicians from the SOV to the wind turbines and vice-versa. One important parameter that needs to be considered as a fundamental concept is the vessel's autonomy which can be expressed according to the volume of fuel, navigation time or distance. The estimation of the available weight that one vessel can transport into a specific route is another important criterion. The CTVs need to perform two types of voyages on the same day. The delivery transfer, in the morning, to drop off the technicians at the turbines and the pick-up transfer in the evening, to collect the technicians at the end of the preventive task. In other words, the SOV is established as an offshore supply base and the CTV as a transportation vessel.

5. The maximum navigation time of each CTV needs to fit the technician's work shift per day.
6. In other to simplify, the calculation of the load factor of each vessel, it is considered that the vessel can carry the full capacity of technicians declared in each model specification sheet.
7. The voyage of each CTV is a round trip that starts and ends at the offshore base per day.

The logistic system described is considered a combinatorial optimization and NP-hard problem, which, accordingly, increases the complexity of integrating into the same model the facility location-allocation problem and the fleet size and mix vehicle routing problem with time window. In this regard, the present paper presents two models aiming at searching for the optimal solutions of these same logistic aspects in a feasible computational time frame. The first model (facility location-allocation model) looks for the optimal placement of the facilities (Port and SOV) that can minimize the infrastructure costs and service costs of the crew transfer vessels to attend each turbine. For this model, the optimal routing is neglected because the main goal is where to locate the offshore base trading off the distances from the onshore base and the turbines. However, the second model (fleet size and mix vehicle-routing with time window model) searches for the optimal sequence of turbines of each crew transfer vessel to deliver and pick up the technicians, also the optimal number of vessels that is necessary to attend the entire wind farm during the preventive period. The solution provides an optimal navigation route table per day and the vessel fleet composition to accommodate the preventive maintenance task. Table 1 schematically presents both conceptual models to provide the main difference between them, and the nomenclature list is presented in the Abbreviations section.

Table 1. Conceptual models.

Models	Facility Location–Allocation Model	Fleet Size and Mix Vehicle-Routing with Time Window Model
Given	The preventive period (in days); the technician's demand per turbine per day; the capacity of the facilities available; the SOV's rental cost; the CTV's variable cost; the CTV's average speed; the CTV's fuel cost per litre; the maximum number of turbines; the turbine's location; maximum inflow of technicians into the SOV; volume of personnel available to work; a large number.	The preventive period (in days); the technician's demand per turbine per day; the capacity of the facilities available; the SOV's rental cost; the CTV's rental cost; the CTV's variable cost; the CTV's average speed; the CTV's fuel cost per litre; the turbine's location; CTV's maximum operational time; maximum allowed passenger flow between vertexes.
Obtain	The distance between the turbines and facilities available (SOVs and ports).	The distance between the turbines and facilities available (SOVs).
Subject to	The turbine assignment constraints; port installation constraints; SOV installation and assignment constraints; technicians' flow constraints.	The vehicle routing constraints; technicians' flow constraints; time window constraints; fleet size constraints.
At minimum	SOV's fixed cost and CTV's variable cost.	SOV's and CTV's fixed costs and CTV's variable cost.

It is important to highlight the impact of the constraint groups on the optimization problem. For the present system, all the modelled constraints have medium-high or high impact on the system modelled. The only medium-high impact constraints are the port installation constraints because, for this system, it is not considered the search for the optimal onshore base location. So, the port installation constraints only assure that the flows of technicians, materials, and vessels from shore to offshore are conserved. However, the other constraints present a high impact on the modelled system.

The turbine assignment constraints ensure that the turbines of the system represent the exact number of turbines planned to be attended, which provides a high impact on the capacity of the offshore base and on the number of vessels designed to perform the maintenance. The technicians' flow constraints guarantee that the outgoing flow from the port to the offshore base and from the offshore base to each turbine is equal to the incoming flow at each node. The vehicle routing constraints ensure that each route is performed by only one vessel and each vessel starts the route at the offshore base, navigates to the maximum allowed turbines per route, which do not violate the vessel's capacity or voyage time and returns to the offshore base. The time window constraints directly impact the voyage time, which is a route restriction due to the technicians' work shifts. Thus, this restriction also impacts the number of transfer vessels to deliver and pick up the technicians. Moreover, the fleet size constraints are also very important for the modelled system because they determine the number of vessels required for the maintenance logistic.

A Mixed-Integer Linear Programming (MILP) formulation is adopted to translate the problems from theory to mathematical language. It means that the objective function is linear and is subject to a set of linear constraints, but the subset of variables takes binary and continuous values. The vehicle routing model with a time window is formulated as an Arc-Flow formulation, which is established on a weighted graph, G = (V, A), representing a transportation network. The nodes are represented as I = {1, j, l, . . . , i }, which is a set of vertexes and the set of arcs.

2.4. Facility Location-Allocation Model

The objective function follows:

$$\text{minimize TotalCost} = \{\text{SOVFixedCost} + \text{CTVVariableCost}\} \tag{1}$$

where

$$SOVFixedCost = \sum_t \sum_s \sum_z y_{tsz} \times SOVRC_{sz} \tag{2}$$

$$\begin{aligned} CTVVariableCost \;&= \left(\sum_t \sum_s \sum_d \left(\frac{DISTA_{tsd}}{CTVSPEED} \right) \times FUELCOST \times CTVFCC \times x_{tsd} \right) \\ &+ \left(\sum_t \sum_s \sum_d \left(\frac{DISTB_{tsd}}{CTVSPEED} \right) \times FUELCOST \times CTVFCC \times x_{tps} \right) \end{aligned} \tag{3}$$

The turbines assignment constraints' group is represented by Equations (4) and (5). Equation (4) guarantees that each turbine is assigned to one offshore base:

$$\sum_{s \in S} x_{tsd} \leq 1 \qquad \forall\, d \in D, t \in T \tag{4}$$

Thus, Equation (5) ensures that the total assignments of turbines cannot exceed the maximum number of turbines:

$$\sum_{s \in S} \sum_{d \in D} x_{tsd} = \text{MAXTURBINES} \qquad \forall\, t \in T \tag{5}$$

The port installation constraints assure that an onshore base must be adopted to support the offshore operation and maintenance activities:

$$\sum_{p \in P} y_p \leq 1 \tag{6}$$

The SOV installation and assignment constraints' group follows:

$$\sum_{S \in S} y_{tsz} \leq 1 \qquad \forall\, s \in S, t \in T \tag{7}$$

$$\sum_{p \in P} x_{tps} \leq 1 \qquad \forall\, s \in S, t \in T \tag{8}$$

$$y_{tsz} \leq \sum_{p \in P} x_{tps} \qquad \forall\, s \in S, t \in T, z \in Z \tag{9}$$

$$\sum_{s \in S} x_{tps} \leq \sum_{s \in S} \text{SOVCAP}_{sz} \times y_{tsz} \qquad \forall\, s \in S, t \in T \tag{10}$$

$$\sum_{s \in S} x_{tps} \leq \text{BIGM} \times y_p \qquad \forall\, p \in P, t \in T \tag{11}$$

Equation (7) establishes that each SOV can only be at most of one size. Equation (8) guarantees that each SOV is assigned to one port. Thus, Equation (9) ensures that if the SOV is installed, it is connected to only one port. The number of turbines assigned to each SOV cannot exceed the SOV capacity, Equation (10). Equation (11) ensures that if the port is assigned to the SOV, the port is installed.

The technician's flow constraints group will fulfil the movement of the passenger's demand, as follows:

$$p_{ts} = \sum_{d \in D} x_{tsd} \times J_{td} \qquad \forall\, s \in S, t \in T \tag{12}$$

$$q_{tp} \leq \sum_{s \in S} r_{tps} \qquad \forall\, p \in P, t \in T \tag{13}$$

$$-p_{ts} + y_{tsz} \leq 0 \qquad \forall\, s \in S, p \in P, t \in T \tag{14}$$

$$-\left(x_{tps} \times \text{PAXMAX}\right) + y_{tsz} \leq 0 \qquad \forall\, s \in S, p \in P, t \in T \tag{15}$$

$$p_{ts} + \left(x_{tps} \times \text{PAXMAX}\right) - y_{tsz} \leq \text{PAXMAX} \qquad \forall\, s \in S, p \in P, t \in T \tag{16}$$

$$\sum_{s \in S} r_{tps} \leq \text{PORTCAP}_p \times y_p \qquad \forall\, p \in P, t \in T \tag{17}$$

The total number of technicians transported to the SOV is the summation of the worker's demand for each turbine, Equation (12). Thus, the total flow of technicians at the port is the summation of the technicians' flow from the SOV to the port, Equations (13)–(16), and the flow of technicians cannot exceed the port capacity, Equation (17).

2.5. Vehicle-Routing Model with Time Window

The objective function follows:

$$\text{minimize TotalCost} = \{\text{SOVFixedCost} + \text{CTVFIXEDCOST} + \text{CTVVariableCost}\} \tag{18}$$

where,

$$\text{SOVFixedCost} = \sum_{s} \sum_{z} y_{tsz} \times \text{SOVRC}_{sz} \tag{19}$$

$$\text{CTVFixedCost} = \sum_{t} \sum_{m} \text{CTVRC}_m \times n_{tm} \tag{20}$$

$$\text{CTVVariableCost} = \left(\sum_{t} \sum_{m} \sum_{v} \sum_{i} \sum_{j} \left(\frac{\text{DIST}_{ij}}{\text{CTVSPEED}_m} \right) \times \text{FUELCOST} \times \text{CTVFCC}_{mv} \times x_{tijmv} \right) \tag{21}$$

The vehicle routing constraints group attempt to ensure the feasibility of the routes:

$$\sum_{i \in I} \sum_{m \in M} \sum_{v \in V} x_{tijmv} \leq 1 \qquad \forall\, t \in T, i \in I, j \in I \mid j > 1 \tag{22}$$

$$\sum_{i \in I} x_{tijmv} - \sum_{l \in I} x_{tjlmv} = 0 \qquad \forall\, t \in T, m \in M, j \in I, v \in V \tag{23}$$

$$u_{ti} - u_{tj} + \left(\text{MAXVERTEX} \times x_{tijmv}\right) \leq \text{MAXVERTEX} - 1 \qquad \forall\, t \in T, m \in M, j \in I, v \in V \;\middle|\; 2 \leq i \neq j \tag{24}$$

Equation (22) of the vehicle routing constraints guarantees that all the turbines will be visited once, Equation (23) ensures the conservation of the route, and Equation (24) fulfils the elimination of sub-tours.

The technician's flow constraints group fulfill the outgoing and incoming flow at each node of the graph:

$$\sum_{i \in I} p_{tij} - \sum_{l \in I} p_{tjl} = J_{ti} \qquad \forall\, t \in T, j \in I \mid j > 1 \tag{25}$$

$$p_{tij} \leq \text{BIGM} \times \sum_{m \in M} \sum_{v \in V} \text{CTVCAP}_{mv} \times x_{tijmv} \qquad \forall\, t \in T, i \in I \mid i = 1, j \in I \mid j > 1 \tag{26}$$

$$p_{tij} \leq \sum_{m}\sum_{v} CTVCAP_{mv} \times x_{tijmv} \qquad \forall\, t \in T, i \in I, j \in I \mid j \neq i \tag{27}$$

$$\sum_{z \in Z} y_{sz} \leq 1 \qquad \forall\, s \in S \tag{28}$$

$$\sum_{i \in I \mid i=1}\ \sum_{j \in I \mid j>1} p_{tij} \leq \sum_{z \in Z} SOVCAP_{sz} \times y_{sz} \qquad \forall\, s \in S, t \in T \tag{29}$$

Equation (25) guarantees the conservation of the difference of passengers between vertexes. Equation (26) ensures that no technicians travel between vertexes if no vehicle performs the route. Equation (27) guarantees that the total technicians' flow cannot exceed the capacity of the vehicle assigned. Thus, Equation (28) establishes that each SOV can only be at most of one size and, Equation (29) ensures that the total technicians' flow at the installed SOV cannot exceed the SOV capacity.

The time window constraints ensure that the route performed does not exceed the operational vessel time window:

$$\sum_{i \in I}\sum_{j \in I}\left(\frac{DIST_{ij}}{CTVSPEED_m}\right) \times x_{tijmv} \leq MAXTIME_{tmv} \qquad \forall\, t \in T, m \in M, v \in V \tag{30}$$

The fleet size constraints group is represented by:

$$l_{tmv} \leq \sum_{j \in I \mid j>1} x_{tijmv} \qquad \forall\, t \in T, m \in M, v \in V, i \in I \mid i=1 \tag{31}$$

$$n_{tm} = \sum_{v \in V} l_{tmv} \qquad \forall\, t \in T, m \in M \tag{32}$$

Equation (31) calculates the total number of travelled routes assigned to the vehicle and, Equation (32) determines the number of vessels needed to accomplish the routes.

3. Case Study, Results, and Discussions

3.1. Case Study

The realistic input data is a result of the work presented by Díaz et al. [21–23], which selected the best location for a floating wind farm on the Spanish coast. Ribadeo is the selected area located in the European Atlantic region in western Europe. The respective Ribadeo port is considered an available onshore base [22]. The authors also determined the number and location of the floating turbines (Figure 2a and Appendix A) [24] as well as the export cable location [25]. Accordingly, from the 88 turbines established, the initial phase of the installation forecasted 28 turbines in the first year, which represents the present case study. Two types of SOVs and CTVs are analyzed in this work. Table 2 presents the main vessel characteristics and cost information. The CTV's average speed is 44.04 knots, and the average number of technicians requested to perform the preventive maintenance task at each turbine is four. The preventive planning horizon is established in three days. Thus, the technicians' workday is considered as 12 h. Furthermore, for the location-allocation model, three possible stand-by points and the group of turbines to be attended for each day are determined (Figure 2b).

Table 2. Vessel's characteristics and cost information.

Vessels	Maximum People (pax)	Wave Limitation (m)	Wind Limitation (m/s)	Velocity (kn)	Daily Costs (US/Day)
CTV-S	12	1.5	25	20	2352.99
CTV-M	15	1.25	20	24	3823.61
SOV-M	50	2	30	12	45,000.00
SOV-L	80	2.5	30	13	67,000.00

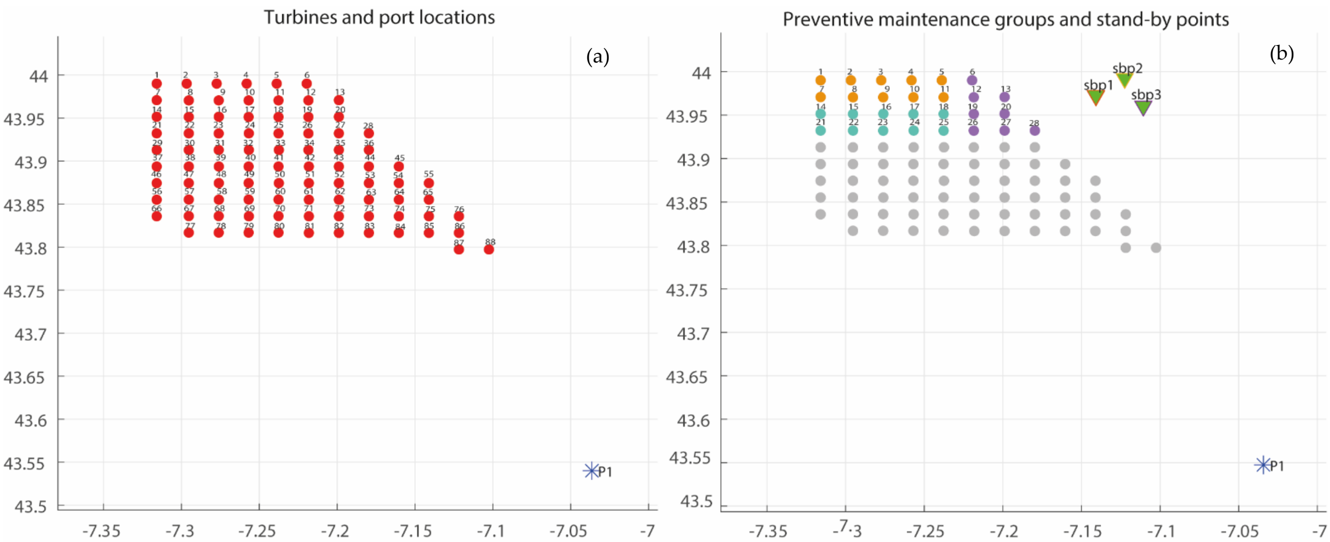

Figure 2. (**a**) Ribadeo floating wind farm layout (**b**) maintenance planning and possible offshore base locations. The asterisk symbol represents the port location.

3.2. Results and Discussions

The mathematical models were implemented and solved by the IBM ILOG CPLEX Studio Optimization. The MILP models were running in a workstation with Intel(R) Core(TM) i7 of 2.30 GHz and 16GB RAM.

The first model attempts only to identify the optimal location of the offshore base considering the distances to the turbines and port. From the three initial possible locations defined above, the model chooses stand-by point one. Figure 3 presents the optimal location solution. Because of the infinite continuous possibility of locations at sea, the search for the optimal offshore base can be complex and timeless. But the model allows the decision-makers to analyze a few possible locations using a rapid screening tool able to generate a solution in less than one minute. Different "what if" scenarios in terms of facility locations, which include the analyses of other onshore bases, can be run without spending a huge computational effort. It is possible to see that the chosen offshore base is the one that most reduce the voyage time of the vessel to attend to the turbines during the maintenance activities, fulfilling the voyage requirements and time window constraints and optimizing the variable cost of the vessels.

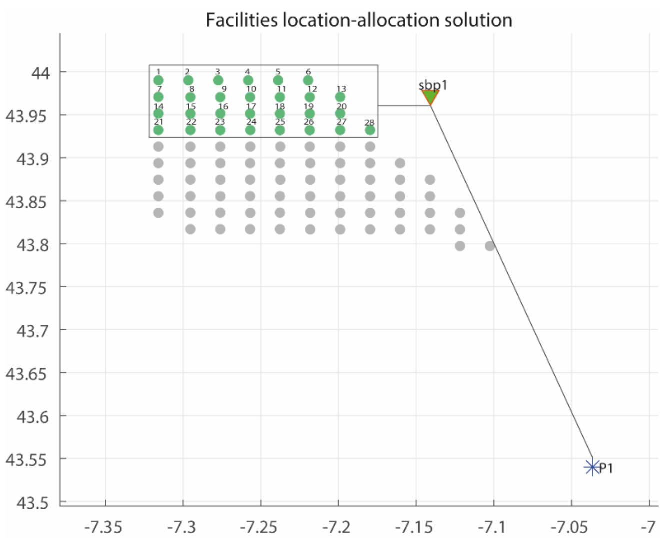

Figure 3. Facility location–allocation solution, where the green dots mean that all the turbines are allocated to the chosen stand-by point.

After establishing the optimal location of the SOV, this solution information turns into input data for the vehicle-routing model with a time window. The optimal navigation routes of each CTV per day and the fleet composition are presented in Table 3, and the graphical representations of the routes per day are shown in Figure 4. Moreover, the cost information of the described logistic is presented in Table 4.

Table 3. Navigation routes per day.

	Routes	Technicians	Utilization (Delivery and Pick-Up Voyages)	Daily Fleet Composition [CTV-S, CTV-M]	Installed SOV [SOV-M, SOV-L]
day one	$i_1 - t_4 - t_3 - t_2 - i_1$	12	1 h 45 min	[1,0]	[1,0]
	$i_1 - t_{11} - t_{10} - t_9 - i_1$	12	1 h 29 min	[1,0]	
	$i_1 - t_5 - i_1$	4	1 h 12 min	[1,0]	
	$i_1 - t_8 - t_7 - t_1 - i_1$	12	2 h 27 min	[1,0]	
day two	$i_1 - t_{13} - t_{14} - t_6 - i_1$	12	1 h 43 min	[1,0]	[1,0]
	$i_1 - t_{20} - t_{19} - t_{26} - i_1$	12	58 min	[1,0]	
	$i_1 - t_{28} - t_{27} - i_1$	8	43 min	[1,0]	
day three	$i_1 - t_{15} - t_{14} - t_{21} - i_1$	12	1 h 30 min	[1,0]	[1,0]
	$i_1 - t_{18} - t_{17} - t_{16} - i_1$	12	1 h 46 min	[1,0]	
	$i_1 - t_{25} - i_1$	4	1 h 07 min	[1,0]	
	$i_1 - t_{24} - t_{23} - t_{22} - i_1$	12	1 h 58 min	[1,0]	

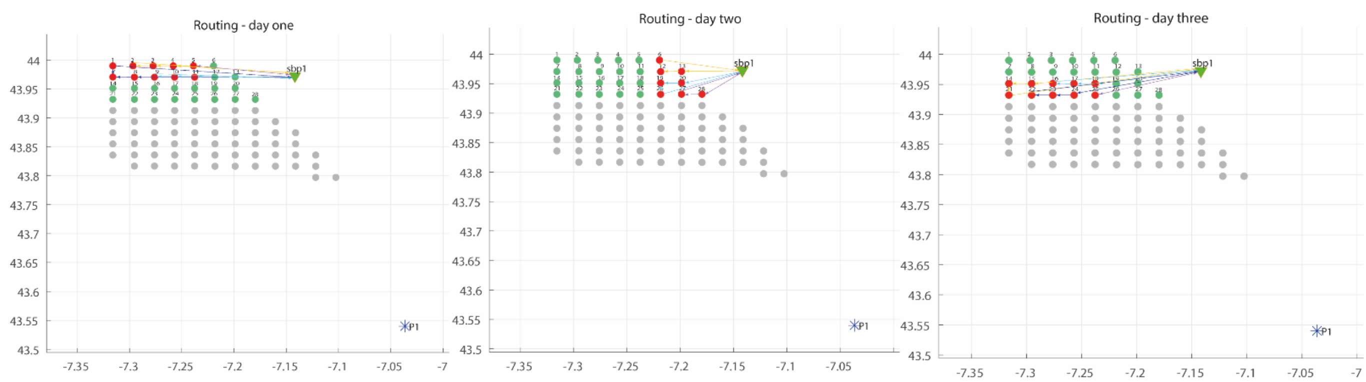

Figure 4. Graphical representation of the routing solutions.

Table 4. Infrastructure costs.

Costs	Value (U$)
SOVFixedCost (U$)	$2.70 \times 10^{+05}$
CTVFixedCost (U$)	$2.59 \times 10^{+04}$
CTVVariableCost (U$)	$1.04 \times 10^{+03}$

The symmetrical nature of the wind farm input data, as well as the equal distance between turbines, the same number of technicians to perform the preventive repairs, and no requirement of task's priority, increases the potential combination of the fleet composition and the time to find an exact solution in a polynomial time. The model defined the optimal daily navigation table, which allows the decision-makers to analyze the routing configuration per day. The main route pattern enforces the CTV to visit three turbines at maximum, delivering and picking up a maximum of 12 technicians. However, it is possible to identify that for day one and day three, there is a single turbine route. It may occur because the capacity of the small CTV (CTV-S) is 12 passengers, and even changing the size of the CTV to transport more technicians (CTV-M, 15 pax) aiming to reduce the single route, become a non-feasible solution due to the total number of technicians to delivery and pick-up at the turbines increases to 16 technicians, which exceeds the available capacities of the CTVs. Therefore, as the optimal solution, the model established that four CTV with the smallest capacity (CTV-S) are enough to perform the routes for three days attending 28 turbines. It proves that the technicians' demand flow constraints are fulfilled even when the CTV visited more than one turbine unit. Additionally, the routes obey the sub-tours elimination constraints and the time window constraints. Also, the model determined that the smallest capacity for the SOV (SOV-M, 50 pax) can accommodate the total of technicians necessary to perform the activities per day, which assures that the total of passengers that leave the SOV is less than the SOV capacity.

In summary, the most important planning insights into the applicability of the methodologies are:

1. The reduction of the computational time and effort of searching for the optimal location of the offshore base by adopting the discrete solution space instead of the continuous solution space, which is infinite.
2. The generation of a navigation route table allows the identification of the routes pattern of the vessels.
3. The daily fleet composition and the respective vehicle's capacity provide bases for cost evaluation and chartering analysis.
4. The combined use of the SOV and CTV appears to be a suitable approach to performing on-time and on-demand services.

4. Conclusions

The recent development of offshore floating wind farms located in deep waters brings new logistic challenges. The main goal of the present study is to integrate the main logistics aspects of the maintenance activities. The facility location–allocation model and the fleet size and mix vehicle routing model with time window provide feasible solutions that increase the planning level of the maintenance activities.

As the main results, from a pool of potential locations pre-defined by the decision-makers, the optimal stand-by point of the offshore base is determined. Afterwards, this solution output is inserted as input for the generation of the optimal navigation table of the vessels to transfer the technicians from the offshore base to the offshore floating turbines. The establishment of the fleet composition and vehicle capacity may guide the decision-makers to analyze the most appropriate type of vessel chartering and investment to maintain the wind farm operations and maintenance activities.

Besides advancing the state of the art, the complexity of the combinatorial nature of the problem brings the limitation of two separate models. However, the results demonstrated that the two screening tools can be useful to help decision-makers in the planning process of maintenance activities.

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Abbreviations

Nomenclature
Location–Allocation Model (MILP)

Sets:	
D	set of turbines;
S	set of SOVs;
P	set of ports;
Z	set of sizes;
T	set of time;
Subscripts:	
d	turbine index;
s	SOV index;
p	port index;
z	size index;
t	time index;
Binary Variables:	
x_{tsd}	assumes the value 1 if the turbine d is allocated to SOV s in time t;
x_{tps}	assumes the value 1 if the SOV s is allocated to port p in time t;
y_p	assumes the value 1 if the port p is installed;
y_{tsz}	assumes the value 1 if the SOV s of size z is installed in time t;
Continuous Variables:	
p_{ts}	total flow of technicians at SOV s in time t;
q_{tp}	total flow of technicians at port p in time t;
r_{tps}	total flow of technicians from SOV s to port p in time t;
Discrete Parameters:	
$DISTA_{tsd}$	distance between the turbines d and SOV s in time t;
$DISTB_{tps}$	distance between the SOV s and port p in time t;
MAXTURBINES	maximum number of turbines;
PAXMAX	volume of personnel available to work;
J_{td}	technicians demand per turbine d in time t;
$PORTCAP_p$	capacity of each available port p;
$SOVCAP_{sz}$	capacity of SOV s of size z;
$SOVRC_{sz}$	rental cost of SOV s of size z;
CTVFCC	fuel consumption cost of CTV;
FUELCOST	fuel cost per litre;
CTVSPEED	average speed of CTV;
BIGM	large number;

Vehicle-Routing Model (MILP)

Sets:	
I	set of vertexes;
S	set of SOVs;
V	set of CTV;
M	set of models;
Z	set of sizes;
T	set of time;
Subscripts:	
i	vertex index;
s	SOV index;
v	CTV index;
m	model index;

z	size index;
t	time index;
Binary Variables:	
y_{tsz}	assumes the value 1 if the SOV s of size z is installed in time t;
Continuous Variables:	
x_{tijmv}	decision to assign the CTV v to travel between vertexes *(i,j)* in time t;
p_{tij}	flow of technicians between vertexes *(i,j)* in time t;
n_{tm}	number of CTV model m
l_{tmv}	number of travels performed by CTV v of model m in time t;
u_{ti}	auxiliary variable assigned to each vertex i in time t;
Discrete Parameters:	
$DIST_{ij}$	distance between vertexes *(i,j)*;
J_{td}	technicians demand per turbine d in time t;
$SOVCAP_{sz}$	capacity of SOV s of size z;
$SOVRC_{sz}$	rental cost of SOV s of size z;
$CTVCAP_{mv}$	capacity of CTV v of model m;
$CTVRC_{m}$	rental cost of CTV's model m;
$CTVFCC_{m}$	fuel consumption cost of CTV's model m;
FUELCOST	fuel cost per litre;
CTVSPEED	average speed of CTV;
$CTVMAXTIME_{tmv}$	maximum CTV v operational time per model m in time t;
BIGM	large number;

Appendix A

Table A1. Location of the turbines.

Turbine	Latitude	Longitude	#N			#N			#N		
1	43.9900	−7.31592	29	43.9129	−7.31592	57	43.8551	−7.28701	85	43.8165	−7.1328
2	43.99003	−7.29664	30	43.91293	−7.28701	58	43.8551	−7.26773	86	43.81655	−7.11353
3	43.99003	−7.27737	31	43.91293	−7.26773	59	43.8551	−7.24846	87	43.79727	−7.11353
4	43.99003	−7.25809	32	43.91293	−7.24846	60	43.8551	−7.22918	88	43.79727	−7.09425
5	43.99003	−7.23882	33	43.91293	−7.22918	61	43.8551	−7.20991	89	43.54006	−7.03641
6	43.99003	−7.21954	34	43.91293	−7.20991	62	43.8551	−7.19063			
7	43.97075	−7.31592	35	43.91293	−7.19063	63	43.8551	−7.17136			
8	43.97075	−7.28701	36	43.91293	−7.17136	64	43.8551	−7.15208			
9	43.97075	−7.26773	37	43.89365	−7.31592	65	43.8551	−7.1328			
10	43.97075	−7.24846	38	43.89365	−7.28701	66	43.8358	−7.31592			
11	43.97075	−7.22918	39	43.89365	−7.26773	67	43.8358	−7.28701			
12	43.97075	−7.20991	40	43.89365	−7.24846	68	43.8358	−7.26773			
13	43.97075	−7.19063	41	43.89365	−7.22918	69	43.8358	−7.24846			
14	43.95148	−7.31592	42	43.89365	−7.20991	70	43.8358	−7.22918			
15	43.95148	−7.28701	43	43.89365	−7.19063	71	43.8358	−7.20991			
16	43.95148	−7.26773	44	43.89365	−7.17136	72	43.8358	−7.19063			

Table A1. *Cont.*

Turbine	Latitude	Longitude	#N			#N			#N
17	43.95148	−7.24846	45	43.89365	−7.15208	73	43.8358	−7.17136	
18	43.95148	−7.22918	46	43.87438	−7.31592	74	43.8358	−7.15208	
19	43.95148	−7.20991	47	43.87438	−7.28701	75	43.8358	−7.1328	
20	43.95148	−7.19063	48	43.87438	−7.26773	76	43.8358	−7.11353	
21	43.9322	−7.31592	49	43.87438	−7.24846	77	43.8165	−7.28701	
22	43.9322	−7.28701	50	43.87438	−7.22918	78	43.8165	−7.26773	
23	43.9322	−7.26773	51	43.87438	−7.20991	79	43.8165	−7.24846	
24	43.9322	−7.24846	52	43.87438	−7.19063	80	43.8165	−7.22918	
25	43.9322	−7.22918	53	43.87438	−7.17136	81	43.8165	−7.20991	
26	43.9322	−7.20991	54	43.87438	−7.15208	82	43.8165	−7.19063	
27	43.9322	−7.19063	55	43.87438	−7.1328	83	43.8165	−7.17136	
28	43.9322	−7.17136	56	43.8551	−7.31592	84	43.8165	−7.15208	

References

1. Yang, L.; Li, G.; Zhang, Z.; Ma, X.; Zhao, Y. Operations & Maintenance Optimization of Wind Turbines Integrating Wind and Aging Information. *IEEE Trans. Sustain. Energy* **2021**, *12*, 211–221. [CrossRef]
2. Hofmann, M. A Review of Decision Support Models for Offshore Wind Farms with an Emphasis on Operation and Maintenance Strategies. *Wind Eng.* **2011**, *35*, 1–16. [CrossRef]
3. Stålhane, M.; Hvattum, L.M.; Skaar, V. Optimization of Routing and Scheduling of Vessels to Perform Maintenance at Offshore Wind Farms. *Energy Procedia* **2015**, *80*, 92–99. [CrossRef]
4. Fan, D.; Ren, Y.; Feng, Q.; Zhu, B.; Liu, Y.; Wang, Z. A hybrid heuristic optimization of maintenance routing and scheduling for offshore wind farms. *J. Loss Prev. Process. Ind.* **2019**, *62*, 103949. [CrossRef]
5. Irawan, C.A.; Ouelhadj, D.; Jones, D.; Stålhane, M.; Sperstad, I.B. Optimisation of maintenance routing and scheduling for offshore wind farms. *Eur. J. Oper. Res.* **2017**, *256*, 76–89. [CrossRef]
6. Gutierrez-Alcoba, A.; Hendrix, E.; Ortega, G.; Halvorsen-Weare, E.; Haugland, D. On offshore wind farm maintenance scheduling for decision support on vessel fleet composition. *Eur. J. Oper. Res.* **2019**, *279*, 124–131. [CrossRef]
7. Gundegjerde, C.; Halvorsen, I.B.; Halvorsen-Weare, E.E.; Hvattum, L.M.; Nonås, L.M. A stochastic fleet size and mix model for maintenance operations at offshore wind farms. *Transp. Res. Part C Emerg. Technol.* **2015**, *52*, 74–92. [CrossRef]
8. Stålhane, M.; Vefsnmo, H.; Halvorsen-Weare, E.E.; Hvattum, L.M.; Nonås, L.M. Vessel Fleet Optimization for Maintenance Operations at Offshore Wind Farms Under Uncertainty. *Energy Procedia* **2016**, *94*, 357–366. [CrossRef]
9. Stålhane, M.; Halvorsen-Weare, E.E.; Nonås, L.M.; Pantuso, G. Optimizing vessel fleet size and mix to support maintenance operations at offshore wind farms. *Eur. J. Oper. Res.* **2019**, *276*, 495–509. [CrossRef]
10. Halvorsen-Weare, E.E.; Gundegjerde, C.; Halvorsen, I.B.; Hvattum, L.M.; Nonås, L.M. Vessel Fleet Analysis for Maintenance Operations at Offshore Wind Farms. *Energy Procedia* **2013**, *35*, 167–176. [CrossRef]
11. Díaz, H.; Guedes Soares, C. Review of the current status, technology and future trends of offshore wind farms. *Ocean Eng.* **2020**, *209*, 107381. [CrossRef]
12. Irawan, C.A.; Starita, S.; Chan, H.K.; Eskandarpour, M.; Reihaneh, M. Routing in offshore wind farms: A multi-period location and maintenance problem with joint use of a service operation vessel and a safe transfer boat. *Eur. J. Oper. Res.* **2023**, *307*, 328–350. [CrossRef]
13. Irawan, C.A.; Salhi, S.; Chan, H.K. A continuous location and maintenance routing problem for offshore wind farms: Mathematical models and hybrid methods. *Comput. Oper. Res.* **2022**, *144*, 105825. [CrossRef]
14. Lazakis, I.; Khan, S. An optimization framework for daily route planning and scheduling of maintenance vessel activities in offshore wind farms. *Ocean Eng.* **2021**, *225*, 108752. [CrossRef]
15. Kang, J.; Guedes Soares, C. An opportunistic maintenance policy for offshore wind farms. *Ocean Eng.* **2020**, *216*, 108075. [CrossRef]
16. Li, H.; Huang, C.-G.; Guedes Soares, C. A real-time inspection and opportunistic maintenance strategies for floating offshore wind turbines. *Ocean Eng.* **2022**, *256*, 111433. [CrossRef]
17. Li, H.; Díaz, H.; Guedes Soares, C. A failure analysis of floating offshore wind turbines using AHP-FMEA methodology. *Ocean Eng.* **2021**, *234*, 109261. [CrossRef]
18. Yang, L.; Chen, Y.; Ma, X. A State-age-dependent Opportunistic Intelligent Maintenance Framework for Wind Turbines Under Dynamic Wind Conditions. *IEEE Trans. Ind. Inform.* **2023**, 1–9. [CrossRef]

19. Díaz, H.; Teixeira, A.; Guedes Soares, C. Application of Monte Carlo and Fuzzy Analytic Hierarchy Processes for ranking floating wind farm locations. *Ocean Eng.* **2022**, *245*, 110453. [CrossRef]
20. Li, H.; Peng, W.W.; Huang, C.-G.; Guedes Soares, C. Failure Rate Assessment for Onshore and Floating Offshore Wind Turbines. *J. Mar. Sci. Eng.* **2022**, *10*, 1965. [CrossRef]
21. Diaz, H.M.; Guedes Soares, C. An integrated GIS approach for site selection of floating offshore wind farms in the Atlantic Continental European coastline. *Renew. Sustain. Energy Rev.* **2020**, *134*, 110328. [CrossRef]
22. Diaz, H.M.; Guedes Soares, C. A novel multi-criteria decision-making model to evaluate floating wind farm locations. *Renew. Energy* **2022**, *185*, 431–454. [CrossRef]
23. Diaz, H.M.; Guedes Soares, C. Approach for installation and logistics of a floating offshore wind farm. *J. Mar. Sci. Eng.* **2023**, *11*, 53. [CrossRef]
24. Diaz, H.M.; Silva, D.; Bernardo, C.; Guedes Soares, C. Micro siting of floating wind turbines in a wind farm using a multiple-criteria framework. *Renew. Energy* **2023**, *204*, 449–474. [CrossRef]
25. Diaz, H.M.; Guedes Soares, C. Multicriteria decision approach to the design of floating wind farm export cables. *Energies* **2022**, *15*, 6593. [CrossRef]