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A Cost Optimisation Model for Maintenance Planning in Offshore Wind Farms with Wind Speed Dependent Failure Rates

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Abstract: This paper presents an optimisation model for cost optimisation of maintenance at an offshore wind farm (OWF). The model is created for OWF project developers to optimise strategic resources to meet their maintenance demand. The model takes into account various maintenance categories on a full range of wind turbine components; the failure rate associated with each component is dependent on wind speed in order to consider weather uncertainty. Weibull distribution is used to predict the probability of wind speed occurring during a given period based on available historical data. The performance of the proposed optimisation model has been validated using reference cases and a UK OWF in operation. Various optimal solutions are investigated for the problems with increased and decreased mean turbine failure rates as a sensitivity test of the model.

Keywords: offshore wind; renewable energy; operations and maintenance (O&M); decision making; cost optimisation

MSC: 90-08

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1. Introduction

For an offshore wind farm (OWF), the operations and maintenance (O&M) activities should be conducted throughout the project life. The O&M activities of offshore wind turbines contribute up to 30% of the energy production cost [1,2], although such costs dislike the huge amount of installation cost during the construction phase. In practice, a major proportion of the O&M costs occur from corrective maintenance activities scheduled to recover the failures on different wind turbine components [3]. Hence, an improvement in the costing performance on corrective maintenance may effectively reduce the energy production costs in OWFs.

During maintenance services in OWFs, one of the common challenges is the transport of technicians, equipment, spare parts and large components to wind turbines offshore [4]. An efficient fleet of transport is required for an offshore wind project, especially to recover wind turbine failures quickly in corrective maintenance. Hence, a large part of O&M costs is spent on purchasing or chartering-in transport, including vessels and helicopters. Transport efficiency plays a key role in determining transport demand in terms of working hours required for fixing different faults by considering vessel/helicopter compatibility and weather restriction. The most popular vessels used in OWF maintenance include crew transfer vessels, field support vessels and jack-up vessels; some other types of vessels might be requested for specialised tasks such as cable-laying [4]. Helicopters are usually considered to take emergency repairs or minor maintenance services in order to help wind turbines re-start work in order after a short breakdown period.

Apart from the purchase or charter-in costs of transportation, a number of other cost elements occurring in maintenance services in OWFs, such as labour costs caused by repair and replacement of turbine components, fuel cost resulting from transport, the repair cost of materials or spare parts and revenue loss due to production downtime [5]. In practice, corrective maintenance management is critical for maximising the availability of production systems and minimising the overall O&M cost [6]. The revenue income loss can be estimated by computing the required service time, the expected waiting time, and the productivity level associated with the probabilistic wind speed. The accessibility of the installed facilities by different transports under various sea states greatly affects the downtime length. Hence, the maintenance of any offshore wind turbines is not simple due to the restricted logistics and accessibility.

An optimal plan of both preventative and corrective maintenance is critical for reducing the O&M cost of an offshore wind farm. The key issue in developing the optimal plan is the decision of how to use the transport and labour to carry out maintenance jobs. A survey of OWF owners was conducted by Pahlke [7], with almost three-quarters of the respondents stating the need for a decision-aiding model/tool, whereas few had existing models for use [5,8]. The existing decision support approaches to date use mainly simulation techniques [8–10]. However, an optimisation solution cannot be derived directly through simulation. Hence, recently a variety of mathematical optimisation models have been developed for the cost minimisation of maintenance planning in offshore wind farms [3,4,11–17]. The most recent research combined mathematical optimisation modelling and simulation techniques [18,19].

The failure rate affects the activity time and costs of transport and labour, especially the corrective maintenance for turbine component breakdown [20,21]. The unscheduled repairs/replacement of failed wind turbine components result in a significant proportion of the maintenance actions, typically between 50–70% [22]. The maintenance practices in an OWF can be optimised with respect to the failure frequency and repairs/replacement costs of wind turbines in the offshore environment. An effectively optimised maintenance schedule for OWFs could potentially reduce the overall maintenance expedition costs to a minimum level in conjunction with the use of historical data on offshore wind turbine failure rates [23].

In this paper, we propose a mathematical optimisation model for OWF developers to improve the cost-effectiveness of conducting maintenance activities. The main objective is to achieve the minimum overall cost incurred in both preventative and corrective maintenance, including transportation, labour, fuel, repair and downtime costs. A variety of wind turbine components are considered under the classification of four categories of maintenance tasks [24]. The contribution of this paper resides in the determination of the failure rates of turbine components, which are expressed as a function of wind speed and the related wind speed probability. To the best of our knowledge, no such study exists in the literature that sets the failure rates of turbine components as a wind-speed-dependent parameter to estimate the maintenance demand. In contrast, a significant relationship exists between wind speed and wind turbine failure rate, according to Wilson and McMillan [25,26]. This relationship needs to be taken into account when the management team is scheduling the corrective maintenance activities for the offshore wind farm.

Although there are many existing decision support tools/systems for optimising OWF maintenance plans, it is not easy to see an algorithm considering wind speed via Weibull distribution. Weibull distribution has been recognised as an effective way to forecast wind speed on the basis of historical data [27]. In the mathematical optimisation model proposed in this paper, the failure rates are differentiated within a range of wind turbine components under four corrective maintenance categories. The wind speed forecasting formula is developed based on Weibull distribution, and the associated energy generation is calculated. The solution of the mathematical optimisation model provides an efficient decision-making approach for optimising and analysing maintenance activities.

The rest of this paper is expressed as follows: In Section 2, a review of existing decision models/tools/algorithms developed for offshore wind farm maintenance is presented. Section 3 introduces the background information on offshore wind farm maintenance, which also gives the essential assumptions of the developed optimisation model. Section 4 describes the proposed OWF maintenance model for optimal strategic planning. Model results and sensitivity analysis are illustrated in Section 5. Finally, some concluding remarks and further research suggestions are given in Section 6.

2. Existing Decision Aid Models for Offshore Wind Farm Maintenance

When modelling O&M practices in OWFs, the failure rate of the wind turbine components is a key parameter that will significantly affect the energy output and cost per unit of energy produced. Several models have been produced to forecast wind power revenue [28] or to predict O&M costs [29,30] by considering wind turbine reliability. Reliability models are utilised to estimate the failure frequency of offshore wind turbines and identify the repair time for each type of failure [31]. The revenue losses due to wind turbine failures and necessary maintenance actions are recognised as the main portion of maintenance costs. This literature review focuses mainly on the development of mathematical optimisation models for the cost minimisation of maintenance planning in offshore wind farms. Operational research (OR) techniques have been used widely in scheduling and capacity planning of renewable energy production [11,32]. For simulation tools to analyse the O&M costs in offshore wind farms, we refer the readers to Hofmann [10] for a survey of decision support models for offshore wind farms with a special emphasis on O&M strategies.

The first mathematical optimisation model that addresses the vessel fleet composition problem for maintenance operations at OWFs was proposed by Halvorsen–Weare et al. [4]. The solution of the model would be used by decision-makers when deciding which vessel type should be purchased or chartered in. The model also helps to determine which infrastructure, such as the maintenance base, should be used to minimise the total cost of the vessel fleet. The model considered uncertain weather parameters, including wind speed, wave heights, wave direction and current, to estimate the spot prices of charter-in contracts and the number of failures that lead to corrective maintenance operations. Finally, they indicated clearly that all these parameters are treated as known in their deterministic model. The work of Halvorsen–Weare et al. [4] has been extended to develop a three-stage stochastic programming model, in which the uncertainty in vessel spot rates, weather conditions, electricity prices and failures are considered. Gundegjerde et al. [12] claimed that these uncertainties are often considered in simulation models, whereas they are mainly handled as deterministic parameters in mathematical programming models. Stålhane et al. [16] applied a two-stage stochastic programming model to help decide the optimal vessel fleet to support maintenance operations at an offshore wind farm.

A number of researchers investigated the optimisation of vessel routes and schedules for maintenance tasks at an offshore wind farm. The problem is similar to a vehicle routing problem with pick-up and delivery [33]. In [34], the fleet of vessels is heterogeneous and located at a depot (base) at the beginning of the planning horizon. The goal is to create one route for each vessel so that the vessel travels from the depot (base) to a set of wind turbines, where it will deliver and pick up technicians and spare parts to perform the maintenance tasks at each turbine. In their problem, the cost function includes travel cost, downtime cost and penalty cost for not performing maintenance tasks in the current time period. The mathematical model is deterministic, and no uncertainties are considered. Their model was later extended to a two-stage stochastic programming model where uncertainty in demand and weather conditions were taken into account [13]. Irawan et al. [14] extended the model in [34] to resolve maintenance routing and scheduling issues within multiple wind farms and O&M bases. This case is relevant to when clusters of neighbouring wind farms are being developed, allowing maintenance resources to be shared between them. In the proposed model, they also took into account different skill types of technicians at each O&M base, the availability of maintenance vessels and spare parts and the capacity of each type of vessel to transfer spare parts.

Although they addressed the weather window to reflect the uncertainty of the weather upon the solution, the weather window has been given as a known value by [34] in their deterministic model. Fan et al. [15] applied mixed particle swarm optimisation to identify a mapping relation between vessels and wind farms and explore the optimal vessel allocation scheme. Based on the scheme of vessel allocation, then, a discrete wolf pack search is introduced for the maintenance route optimisation under all constraints.

Most recently, to handle the uncertainties of weather conditions and turbine failure rate in offshore wind turbine maintenance, Irawan et al. [19] proposed a sim-metaheuristic algorithm which combines a metaheuristic with Monte Carlo simulation to solve the stochastic maintenance routing problem. The Monte Carlo simulation takes a number of uncertainties into consideration: weather conditions, the condition of the turbine, technicians' skills, vessel conditions and the weight of equipment/parts. Turan et al. [18] combined system dynamics and discrete event simulation approaches to model and solve a strategic problem of fleet renewal to match future requirements under uncertain conditions. The uncertainties considered are resource uncertainties. Li et al. [35] considered more uncertainties in OWF failure to generate a multi-objective OWF maintenance strategy optimisation framework by using a probabilistic method and the Monte Carlo method.

The most relevant paper to the proposed research is the one by Li et al. [3]. In the paper, the decisions need to be made on the maintenance strategies to select for OWF developers, the number of technicians for HR managers and the number of chartered vessels for O&M planners. The objective is to pursue a minimum total cost of personnel, transport and breakdown for O&M in offshore wind farms. Li et al. [3] developed both deterministic and stochastic optimisation models for this problem. The deterministic optimisation model is used when the failure rates of wind turbine components are given, whilst the stochastic model is utilised in case accurate failure data is unavailable.

From the review of the existing optimisation models for maintenance in OWFs, there is scarce research in the literature that sets the failure rates of turbine components as a weather-based parameter to estimate the maintenance demand. The main contribution is to link the failure rates of turbine components with wind speed and the related wind speed probability. The new mathematical optimisation model proposed in this paper concentrates on corrective maintenance activities in an offshore wind farm since they are more sensitive to weather variations. The objective of the optimisation model is to minimise the overall maintenance cost with a wider range of cost elements resulting from labour, transport, fuel, repair/replacement and downtime in practice. Different wind speed levels are considered with an occurrence probability based on the historical data; modified model constraints will correspond to estimated failure rates with the probabilistic wind speed.

3. OWF Maintenance Characteristics and Assumptions of the Optimisation Model

The proposed model focuses on minimising the expected maintenance costs of an offshore wind farm during a given period. A range of maintenance categories is specified technically on wind turbine components. Different kinds of transport from a base port, including vessels and helicopters, are used to execute the maintenance work at a single offshore wind farm. The travel distance is a return journey between the base port and the offshore wind farm, as shown in Figure 1. Maintenance technicians are hired on either a full-time or part-time basis. Wind speed probability, as a key parameter of sea state, is predicted by using Weibull distribution. This parameter is crucial to predict turbine failures and to determine the expected energy production.

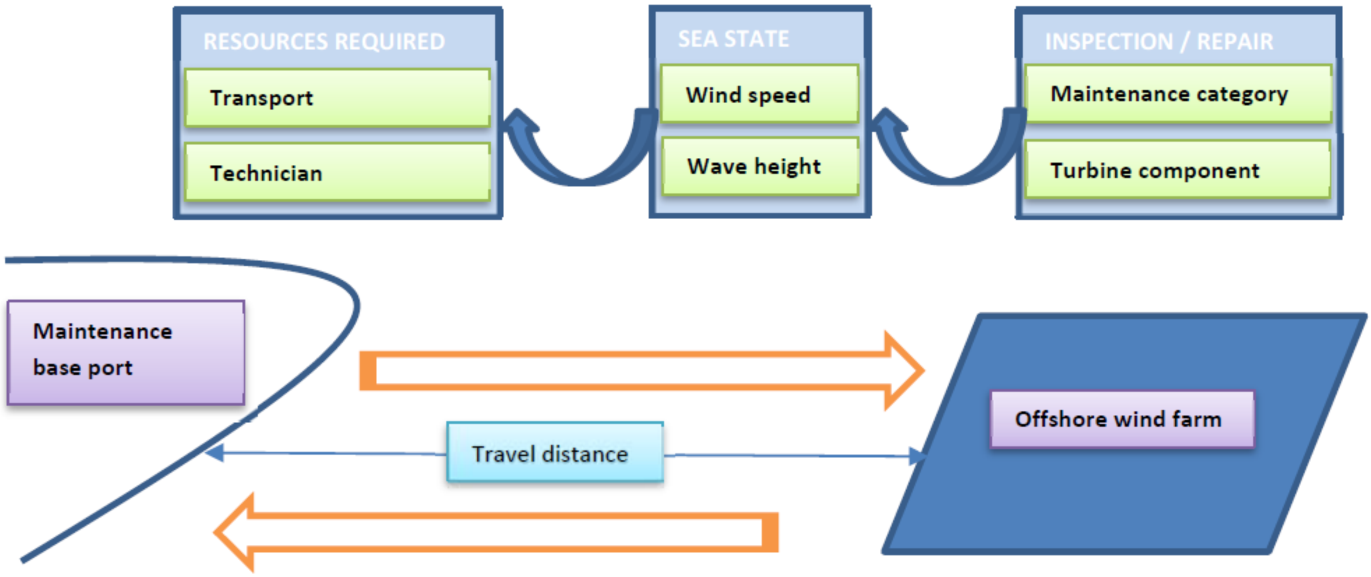

Figure 1. Offshore wind farm maintenance decision-making workflow.

Based on the weather-based failure rates on each turbine component in a given OWF size, the required number of transports and technicians would be balanced by the model with the minimised total amount of annual cost. Maintenance demand, vessel/helicopter compatibility and sea state restriction on transport are considered in the transport selection and cost minimisation. Figure 2 shows the workflow of the proposed optimisation model with its inputs and outputs. The overall workflow of the optimisation model considers two sets of input parameters, namely OWF data and maintenance technical data. The wind speed via Weibull distribution, with historical weather data, is used to determine the power generation and failure frequency. The input of OWF maintenance data, such as transport compatibility and deployability, will be picked to meet the maintenance requirement. On a given actual problem, the maintenance technical data could be altered by using its realistic values in the proposed model. After implementing the model, the demand for transport and technicians is estimated, and the minimised costs are computed.

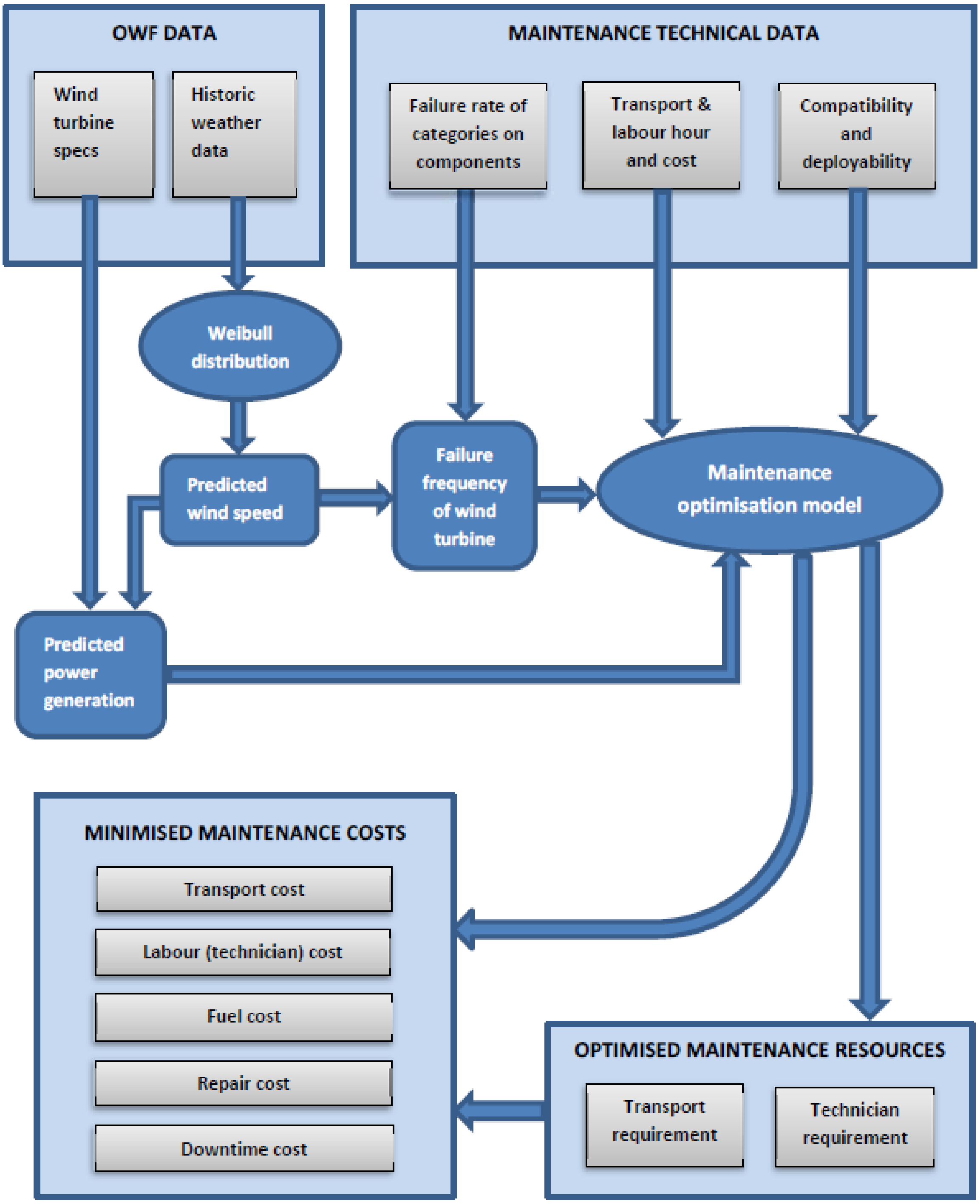

Figure 2. Workflow of the proposed maintenance optimisation model.

3.1. Categorisation of Maintenance on Wind Turbine Components

The developed optimisation model takes into account both preventative and corrective maintenance. Different categories of maintenance activities, such as minor repair and major replacement, are allocated to a range of key turbine components. Index i denotes the maintenance category, and j represents the component. All key components of a wind turbine, such as a gearbox and rotor blade, are considered in the maintenance activities of the model.

For each maintenance category on every wind turbine component, the repair time, repair cost and the number of technicians required are determined (Carroll et al., 2016).

Repair time (T_{ij}^{repair}) covers the time that the maintenance technicians use during inspection, repair or replacement. Repair cost (C_{ij}^{repair}) is the cost of materials, equipment and tools. In addition, the number of required technicians (Q_{ij}) is also pre-determined depending on the workload of each maintenance category on different wind turbine components. The travel time of a vessel or helicopter from the maintenance base port to the offshore wind farm is defined as $T_k^{travel} = \frac{2D}{S_k}$ by the travel distance of a returned trip over the transport speed.

3.2. Compatibility and Deployability of Maintenance Transport

The main activities in offshore wind maintenance are the transport of the technicians, materials and spare parts and the execution of service, repair or replacement. The compatibility and deployability of maintenance transport are recognised with OWF practitioners in the 2OM (Offshore Operations & Management Mutualisation) project.

A range of transport means, including vessels and helicopters, are used to execute different maintenance tasks on the wind turbine components. Index k denotes the common transportation type used in offshore wind maintenance. The most suitable transport type should be selected to execute a maintenance job subject to the compatibility of transport and weather restrictions. Different wind speed levels (w) are considered to investigate the impact of failure rate on energy productivity.

Vessels and/or helicopters can be chartered, on a short-term or long-term lease, to carry out maintenance tasks during the planning horizon. According to the response in interviews with OWF practitioners, each type of transport has a given fixed cost (C_k^{fixed}), charter cost ($C_k^{charter}$), fuel consumption (O_k), fuel cost (C_k^{fuel}) and transport speed (S_k). The length of the lease period in hours ($H_k^{transport}$) of each transportation type is pre-determined in the developed model. In addition, the labour hours of a full-time technician ($H_k^{labourFT}$) and a part-time technician ($H_k^{labourPT}$) are introduced as working time in one year and three months, respectively. Hence, the labour cost per full-time technician ($C_k^{labourFT}$) and part-time technician ($C_k^{labourPT}$) working on each transport type is defined as the annual and quarterly salaries.

A maintenance team is usually sent to execute a task; the number of technicians (Q_{ij}) in a team depends on the workload of maintenance category i on component j. Each maintenance category requires compatible transportation. For instance, a major replacement of large turbine components must be executed by a heavy vessel with a crane. The OWF practitioners also introduced the two binary parameters of compatibility and deployability. A binary parameter ($B_{ik}^{compatible}$) is used to express the compatibility of transport type k on maintenance category i. The use of transportation means also considers the sea state, wind speed acts as a key parameter to determine whether a transport type can go to execute maintenance work. If the wind speed reaches the operational limit of the suitable transports, the maintenance activities will be postponed. Hence, another binary ($B_{kw}^{deployable}$) is defined to show the deployability of each transport type k under wind speed w. The selection of transport type must be subject to the binary variable of both compatibility on maintenance categories and deployability on wind speeds.

3.3. Wind Speed Dependent Failure Rates

A significant relationship exists between the wind speed and the wind turbine failure rate. Wilson and McMillan [25] proposed that the failure rates could be computed as a function of wind speed, and they then developed the following model of wind speed-dependent failure rates to assess wind farm reliability.

$$\lambda_{ij,w}^{fail|wind} = \frac{Prob_{w,ij}^{wind|fail} \cdot F_{ij}}{Prob_{w}^{wind}} \quad (1)$$

$Prob_{w,ij}^{wind|fail}$ is the probability of wind speed w occurring, given a failure category i has occurred to component j. It could be calculated by taking a probability density function of average wind speed recorded on days when a failure occurred. F_{ij} is the mean failure rate of category i on component j. $Prob_w^{wind}$ represents the probability that the average wind speed is w. Therefore, Equation (1) is used to calculate the probability of a failure to category i of component j, given an average wind speed w. The key advantage of using this model is that the effect of seasonal changes on wind turbine operation can be accounted for.

3.4. Weibull Distribution to Predict Wind Speed Probabilities

As a common method to forecast wind speed probability, the Weibull distribution provides a close approximation and has been used to represent wind speed distribution for many applications of wind sources [27]. Its greater flexibility and simplicity make it ideal for experimental data [36]. The Weibull distribution function, as a two-parameter function for wind speed probability, is expressed in Equation (2).

$$Prob_w^{wind} = \left(\frac{m}{c}\right)\left(\frac{w}{c}\right)^{m-1} exp\left(-\left(\frac{w}{c}\right)^{m}\right) \quad (2)$$

where w is the wind speed, m is the shape parameter and c is the scale parameter. A range of methods can be applied to determine the value of the parameters, such as the empirical method, maximum likelihood method and graphical method [36,37].

3.5. Energy Generation with Different Wind Speeds

The available energy generation rate of an offshore wind turbine varies with different wind speeds. Cut-in (WS^{in}) and cut-out (WS^{out}) wind speeds specify the minimum and maximum wind speeds that the turbine can work to generate energy. If wind speed is less than the cut-in level or greater than the cut-out level of a specific wind turbine model, then the turbine terminates energy generation. The energy production rate keeps increasing with the strength of the wind between cut-in and rated wind speeds. The rated wind speed (WS^{rated}) provides sufficient wind power that the turbine works with the rated capacity (Cap^{rated}). The production rate is stable at the rated capacity level when the wind speed is over the technically rated wind speed until the cut-out level. A common formula, expressed in Equation (3), is used to calculate how much power could be generated in one hour by a given wind turbine under wind speed w.

$$G_w^{avail}(WS_w) = \begin{cases} 0,\ WS_w < WS^{in} \\ \frac{1}{2} \cdot \rho \cdot A \cdot (WS_w)^3 \cdot Coe^p,\ WS^{in} \le WS_w < WS^{rated} \\ Cap^{rated},\ WS^{rated} \le WS_w \le WS^{out} \\ 0,\ WS_w > WS^{out} \end{cases} \quad (3)$$

Sweep area (A) is usually determined by the length of the turbine blade. Air density (ρ) and wind speed (WS_w) are core parameters in the energy production formula. The value of the power coefficient (Coe^p) is unique to each wind turbine and is a function of the wind speed of the turbine. The Betz Limit [38] specified that 0.59 is the theoretically maximum power coefficient of any design of a turbine. The realistic power coefficient is significantly below the Betz Limit; values between 0.35 and 0.45 are common in the best-designed wind turbines.

4. The Optimisation Model Formulation

The optimisation model aims to minimise the overall cost, which includes the following costs: transportation, labour, fuel consumption, repair cost and downtime.

- Transport fixed cost: Transport fixed cost includes one-off costs during an agreed charter period of a vessel or helicopter, such as insurance, maintenance, etc. The cost for each transport type k is computed by the unit fixed cost of a charter period and the number of lease charters on this transport type required for repair/replacement works.

$$Transport\ fixed\ cost = C_k^{fixed} \cdot x_k^{\alpha} \quad (4)$$

- Labour cost: Full-time technicians are charged on the basis of an annual salary; part-time technicians are assumed to take a short-term contract every quarter. Short-term temporary employment provides the flexibility to hire more technicians during the busy seasons. However, the salary of quarterly contracts comes with a 37.5% extra from the annual salary rate. Then, the total labour cost of each transportation k is determined by the full-time and part-time salary ($C_k^{labourFT}$ and $C_k^{labourPT}$) with the number of technicians employed ($y_k^{FT,\alpha}$ and $y_k^{PT,\alpha}$) for undertaking maintenance activities.

$$Labour\ cost = C_k^{labourFT} \cdot y_k^{FT,\alpha} + C_k^{labourPT} \cdot y_k^{PT,\alpha} \quad (5)$$

- Transport charter cost: The total charter cost of transport type k is determined in terms of a daily charter rate ($C_k^{charter}$) and the length of chartering period. As a popular transport type in OWF maintenance, crew transfer vessels are assumed to be chartered on an annual basis. Field support vessels and jack-up vessels are usually chartered weekly when a major repair or replacement is required. Helicopters are required in the case of urgent maintenance demand; they are chartered on the basis of the number of hours. The number of charter periods for each transport type must be multiple of a work shift, L_k^{shift} is the working hours in a daily shift.

$$Transport\ charter\ cost = C_k^{charter} \cdot \left\lceil \frac{\left(T_k^{travel} + T_{ij}^{repair}\right) \cdot z_{ijkw}}{L_k^{shift}} \right\rceil \quad (6)$$

where z_{ijkw} is a binary variable whether transport type k is selected for maintenance category i on component j under wind speed w

- Transport fuel cost: The fuel cost rate (C_k^{fuel}) is defined per m^3 for each transport type k. Fuel consumption of a specific transport (O_k) is estimated per hour of travel time.

$$Transport\ fuel\ cost = C_k^{fuel} \cdot O_k \cdot T_k^{travel} \cdot z_{ijkw} \quad (7)$$

- Repair cost: Repair cost is the direct maintenance cost of repair materials, spare parts and equipment. The total amount of repair cost should be determined by the unit cost (C_{ij}^{repair}) of category i on component j, with the maintenance demand that is dependent on the failure rate.

$$Repair\ cost = C_{ij}^{repair} \cdot \lambda_{ij,w}^{fail|wind} \cdot N \quad (8)$$

- Downtime cost: Any revenue loss due to the breakdown of turbines is defined as downtime cost, which is computed by the hourly income of wind power production (C^{down}) and the length of downtime, including travel time, repair time and waiting time of each maintenance task. A single trip travel time ($\frac{T_k^{travel}}{2}$) of the selected transport k is accounted-for downtime. The length of repair time (T_{ij}^{repair}) is given as a constant of the maintenance category i on turbine component j. It is not related to the type of transportation used.

$$downtime\ cost = C^{down} \cdot G_w^{avail} \cdot \left(\frac{T_k^{travel}}{2} + T_{ij}^{repair} + T_{kw}^{wait}\right) \cdot z_{ijkw} \quad (9)$$

The objective function of the model is to minimise the sum of the two fixed costs and four expected variable costs.

$$\begin{aligned} Min\ Total\ Cost = & \sum_{k\in K} C_k^{fixed} \cdot x_k^{\alpha} + \sum_{k\in K} C_k^{labourFT} \cdot y_k^{FT,\alpha} + \sum_{k\in K} C_k^{labourPT} \cdot y_k^{PT,\alpha} \\ & + \sum_{i\in I}\sum_{j\in J}\sum_{k\in K}\sum_{w\in W} C_k^{charter} \cdot \left\lceil \frac{\left(T_k^{travel} + T_{ij}^{repair}\right) \cdot z_{ijkw} \cdot \lambda_{ij,w}^{fail|wind} \cdot N}{L_k^{shift}} \right\rceil \\ & + \sum_{i\in I}\sum_{j\in J}\sum_{k\in K}\sum_{w\in W} C_k^{fuel} \cdot O_k \cdot T_k^{travel} \cdot z_{ijkw} \cdot \lambda_{ij,w}^{fail|wind} \cdot N \\ & + \sum_{i\in I}\sum_{j\in J}\sum_{w\in W} C_{ij}^{repair} \cdot \lambda_{ij,w}^{fail|wind} \cdot N \\ & + \sum_{i\in I}\sum_{j\in J}\sum_{k\in K}\sum_{w\in W} C^{down} \cdot G_w^{avail} \cdot \left(\frac{T_k^{travel}}{2} + T_{ij}^{repair} + T_{kw}^{wait}\right) \cdot z_{ijkw} \cdot \lambda_{ij,w}^{fail|wind} \cdot N \end{aligned} \quad (10)$$

Constraints:

The above objective function of minimising the total cost should be achieved subject to a variety of constraints in O&M for the use of vessels/helicopters and technicians. In order to hire enough length of transportation and labour times to execute maintenance works, both transport hours (constraint set 1(a)–1(d) and labour hours (constraint set 2(a)–2(d)) should cover the requirement of different maintenance categories on turbine components. The repair time (T_{ij}^{repair}) and the travel time (T_k^{travel}) are the two major portions to estimate the length of the required time of transport type *k*.

Constraint set 1(a): The total available time of each transport type *k* must be greater than the length of the working time required, including travel and repair/replacement, for undertaking maintenance.

$$x_k^{\alpha} \cdot H_k^{transport} \geq \sum_{i\in I}\sum_{j\in J}\sum_{w\in W} \left(T_{ij}^{repair} + T_k^{travel}\right) \cdot z_{ijkw} \cdot \lambda_{ij,w}^{fail|wind} \cdot N\ \ \forall\ k \in K \quad (11)$$

Constraint set 1(b): The available time of each transport type *k* used for maintenance category *i* must be greater than the length of the working time required, including travel and repair/replacement, for undertaking maintenance.

$$x_{ik}^{\beta} \cdot H_k^{transport} \geq \sum_{j\in J}\sum_{w\in W} \left(T_{ij}^{repair} + T_k^{travel}\right) \cdot z_{ijkw} \cdot \lambda_{ij,w}^{fail|wind} \cdot N\ \ \forall\ i \in I, k \in K \quad (12)$$

Constraint set 1(c): The available time of each transport type *k* used for maintenance category *i* on turbine component *j* must be greater than the length of the working time required, including travel and repair/replacement, for undertaking maintenance.

$$x_{ijk}^{\gamma} \cdot H_k^{transport} \geq \sum_{w\in W} \left(T_{ij}^{repair} + T_k^{travel}\right) \cdot z_{ijkw} \cdot \lambda_{ij,w}^{fail|wind} \cdot N\ \ \forall\ i \in I, j \in J, k \in K \quad (13)$$

Constraint set 1(d): The available time of each transport type *k* used for maintenance category *i* on turbine component *j* under wind speed *w* must be greater than the length of working time required, including travel and repair/replacement, for undertaking maintenance.

$$x_{ijkw}^{\delta} \cdot H_k^{transport} \geq \left(T_{ij}^{repair} + T_k^{travel}\right) \cdot z_{ijkw} \cdot \lambda_{ij,w}^{fail|wind} \cdot N\ \forall\ i \in I, j \in J, k \in K, w \in W \quad (14)$$

where

$$x_k^{\alpha} \geq x_{ik}^{\beta} \geq x_{ijk}^{\gamma} \geq x_{ijkw}^{\delta} \quad (15)$$

Constraint set 2(a): The available labour hours for both full-time and part-time technicians on transport k should cover the travel and repair/replacement of maintenance executed by the transport.

$$y_k^{FT,\alpha} \cdot H_k^{labourFT} + y_k^{PT,\alpha} \cdot H_k^{labourPT} \geq \sum_{i\in I}\sum_{j\in J}\sum_{w\in W}\left(T_{ij}^{repair} + T_k^{travel}\right) \cdot z_{ijkw} \cdot \lambda_{ij,w}^{fail|wind} \cdot N \quad \forall\, k \in K \tag{16}$$

Constraint set 2(b): The available labour hours for both full-time and part-time technicians on transport k should cover the travel and repair/replacement of maintenance category i executed by the transport.

$$y_{ik}^{FT,\beta} \cdot H_k^{labourFT} + y_{ik}^{PT,\beta} \cdot H_k^{labourPT} \geq \sum_{j\in J}\sum_{w\in W}\left(T_{ij}^{repair} + T_k^{travel}\right) \cdot z_{ijkw} \cdot \lambda_{ij,w}^{fail|wind} \cdot N \quad \forall\, i \in I, k \in K \tag{17}$$

Constraint set 2(c): The available labour hours for both full-time and part-time technicians on transport k should cover the travel and repair/replacement of maintenance category i on component j executed by the transport.

$$y_{ijk}^{FT,\gamma} \cdot H_k^{labourFT} + y_{ijk}^{PT,\gamma} \cdot H_k^{labourPT} \geq \sum_{w\in W}\left(T_{ij}^{repair} + T_k^{travel}\right) \cdot z_{ijkw} \cdot \lambda_{ij,w}^{fail|wind} \cdot N \quad \forall\, i \in I, j \in J, k \in K \tag{18}$$

Constraint set 2(d): The available labour hours for both full-time and part-time technicians on transport k should cover the travel and repair/replacement of maintenance category i on component j under wind speed w executed by the transport.

$$y_{ijkw}^{FT,\delta} \cdot H_k^{labourFT} + y_{ijkw}^{PT,\delta} \cdot H_k^{labourPT} \geq \left(T_{ij}^{repair} + T_k^{travel}\right) \cdot z_{ijkw} \cdot \lambda_{ij,w}^{fail|wind} \cdot N \quad \forall\, i \in I, j \in J, k \in K, w \in W \tag{19}$$

where

$$y_k^{FT,\alpha} \geq y_{ik}^{FT,\beta} \geq y_{ijk}^{FT,\gamma} \geq y_{ijkw}^{FT,\delta} \tag{20}$$

$$y_k^{PT,\alpha} \geq y_{ik}^{PT,\beta} \geq y_{ijk}^{PT,\gamma} \geq y_{ijkw}^{PT,\delta} \tag{21}$$

Constraint set 3: The total number of full-time and part-time technicians on transport k must be at least equal to the number required to carry any maintenance category i on wind turbine component j if the transport is selected to execute the work under wind speed w.

$$y_{ijkw}^{FT,\delta} + y_{ijkw}^{PT,\delta} \geq Q_{ij} \cdot z_{ijkw} \quad \forall\, i \in I, j \in J, k \in K, w \in W \tag{22}$$

Constraint set 4: Transport type k can be used to execute maintenance category i on component j under wind speed w only if the transport type is compatible with the maintenance category and deployable under the weather condition.

$$z_{ijkw} \leq B_{ik}^{compatible} \times B_{kw}^{deployable} \quad \forall\, i \in I, j \in J, k \in K, w \in W \tag{23}$$

Constraint set 5: A binary variable is used to indicate whether transport type k is selected to execute maintenance category i on component j under wind speed w. If transport type k is not selected for any category of maintenance on any wind turbine component under any wind speed, the number of the transport must be zero.

$$x_{ijkw}^{\delta} \leq M \cdot z_{ijkw} \text{ and } x_{ijkw}^{\delta} \geq z_{ijkw} \quad \forall i \in I, j \in J, k \in K, w \in W \tag{24}$$

where M is a large positive number.

Constraint set 6: Each maintenance job of category i on component j under wind speed w must be served by at least one type of transport if the failure rate is greater than zero and compatible transports are available.

$$\sum_{k\in K} z_{ijkw} \geq \sum_{k\in K} \lambda_{ij,w}^{fail|wind} \cdot B_{ik}^{compatible} \qquad \forall i \in I, j \in J, w \in W \tag{25}$$

The optimisation model provides cost-effective planning for the maintenance operations of one offshore wind farm. It can be used to select the right type(s) of maintenance transport and technicians and to determine the optimal amount of transport charters and technicians for executing requested maintenance activities with the minimised total cost.

5. Experimental Results

A series of reference cases, initially published in [39], was applied to the developed model for validation. Rampion offshore wind farm is used, as a sample case study, to verify this optimisation model. The optimisation model has been solved by minimising multiple types of costs. Experimental results and sensitivity analysis are presented in this section.

5.1. Data Setting

According to Carroll et al.'s categorisation of corrective maintenance activities [24], four categories of corrective and preventative tasks (in Figure 3) are allocated to the maintenance of the nineteen wind turbine components (in Table 1). Maintenance frequency for the corrective maintenance depends significantly on the component failure rates. The essential characteristics of the four corrective maintenance categories of the nineteen wind turbine components in the developed model are collected from the research work in [24], including mean failure rate, repair time, repair cost and the number of technicians required.

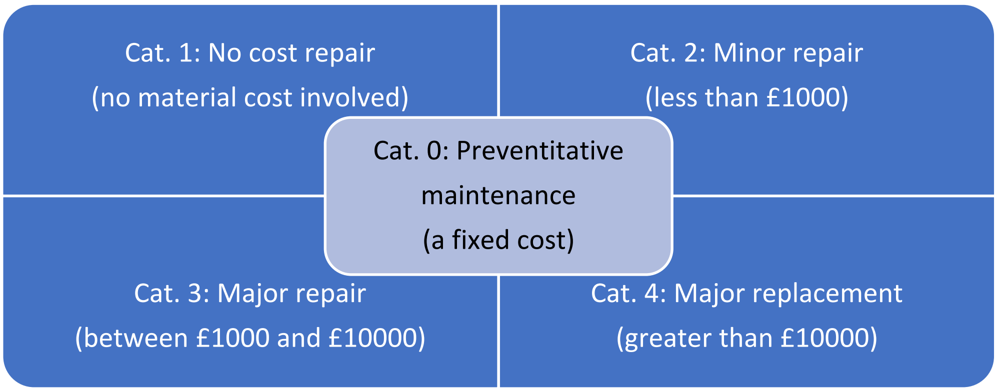

Figure 3. Categorisation of the maintenance on offshore wind turbines.

Table 1. List of key turbine components (Carroll et al., 2016).

Comp.1	Pitch system	Comp.11	Pumps/motors
Comp.2	Generator	Comp.12	Hub
Comp.3	Gearbox	Comp.13	Heating/cooling system
Comp.4	Rotor blades	Comp.14	Yaw system
Comp.5	Grease oil/cooling liquid	Comp.15	Tower/foundation
Comp.6	Electrical components	Comp.16	Power supply/converter
Comp.7	Contactor/circuit breaker	Comp.17	Transformer
Comp.8	Control system	Comp.18	Service items
Comp.9	Safety system	Comp.19	Other components
Comp.10	Sensors		

A range of transport types are used to execute different maintenance tasks on the wind turbine components; type $k = 1 \ldots 4$ denote the four common transportation means, namely crew transfer vessel (CTV), field support vessel (FSV), jack-up vessel (JUV) and helicopter (HEL). CTVs are popular for working in the offshore energy field, such as oil and gas. FSVs and JUVs are used to take large repair and/or heavy wind turbine components. HELs can support the transportation of technicians and small spare parts in emergencies and can significantly reduce the length of downtime. According to the data acquired from O&M practice in the sector, the binary variable ($B_{ik}^{compatible}$) of compatibility of transport k for maintenance category i is clarified in Table 2. The value of 1 indicates 'compatible', and 0 represents 'incompatible'. Based on the technical knowledge, in addition, the technicians working on field support vessels and jack-up vessels can be used on crew transfer vessels for minor repairs.

Table 2. Compatibility of each transport type on maintenance categories.

$\boldsymbol{B_{ik}^{compatible}}$	*CTV*	*FSV*	*JUV*	*HEL*
CAT.0	1	1	1	1
CAT.1	1	1	1	1
CAT.2	1	1	1	1
CAT.3	0	1	1	0
CAT.4	0	0	1	0

The use of the maintenance transport is also subject to weather restrictions. The wind speeds $w = 1 \ldots 22$ are considered to investigate the impact of failure rate on energy productivity. The binary variable ($B_{kw}^{deployable}$) is shown in Table 3 to describe the deployability of each transport type under different wind speeds. By considering safety, for instance, a jack-up vessel is not allowed to operate a heavy lift for a major replacement if the wind speed is over 15 m/s.

Table 3. Deployability of each transport type on wind speeds (1–22 m/s).

$\boldsymbol{B_{kw}^{deployable}}$	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*11*	*12*	*13*	*14*	*15*	*16*	*17*	*18*	*19*	*20*	*21*	*22*
CTV	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
FSV	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
JUV	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0
HEL	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0

The rest of the standard industrial data are summarised from the work of Dalgic et al. [40], such as transportation fixed cost, transport charter cost, transport fuel consumption, fuel unit cost, labour cost, transport speed, transport restriction by wind speed and usual transport charter period. The wind turbine specifications, such as rated capacity and rated wind speed, are available on several websites (i.e., http://4cOffshore.com, accessed on 15 May 2020). To achieve the expected solution in different cases by using the developed optimisation model, perhaps it is necessary to amend the model parameters with updated data on industrial operations and the market.

5.2. Validation of the Developed Model Based on a Reference Case

The proposed model has been evaluated, and its performance has been compared with other existing models published in [39]. The study uses a number of reference cases to verify four decision-making models for OWF maintenance as follows: the Strathclyde analysis tool, the NOWIcob decision support tool, the University of Stavanger (UiS) Simulation model and the ECUME model. A case study of an OWF that consists of eighty (80) 3.0 MW wind turbines, which is developed 50 km from an onshore maintenance port. Three types of vessels were considered to execute the annual preventative maintenance and four categories of corrective maintenance, including manual resets, minor repair, medium repair and major repair/replacement. Three CTVs, one FSV and one heavy-lift vessel are available in the maintenance base port.

A comparative analysis has been conducted to compare the proposed model (new model) with the models in the literature, as shown in Table 4. There are two main cost components, which are the annual loss of production and the annual direct O&M cost. The direct O&M cost contains vessel cost, repair cost and technician cost. By comparing the base case results, the annual loss of production from this new model, £19.27 million, is slightly higher than other models, which is based on the predicted power generation with stochastic wind speeds. The direct O&M cost indicates that the result (£19.35 million) from the newly developed model stays at the median level of these five models. Of the three elements, only the repair cost stays at the highest level.

Table 4. Comparison of cost results in the base case between models.

	New Model	*Strathclyde CDT*	*NOWIcob*	*UiS Sim Model*	*ECUME Model*
Annual loss of production	**£19.27m**	**£17.28m**	**£16.63m**	**£15.48m**	**£18.64m**
Annual direct O&M cost	**£19.35m**	**£22.44m**	**£25.17m**	**£17.92m**	**£14.48m**
Annual vessel cost	£13.25m	£17.84m	£19.18m	£12.24m	£9.30m
Annual repair cost	£4.50m	£3.00m	£4.39m	£4.08m	£3.58m
Annual technician cost	£1.60m	£1.60m	£1.60m	£1.60m	£1.60m

Several further cases were generated from the base case for investigating the quantitative sensitivity, including more (5) CTVs and fewer (1) CTVs, more (30) and fewer (10) technicians and failure rates down (50%) and up (200%). Figure 3 shows direct O&M costs for the base case and the other cases. By comparing with the results of the other four models presented by Dinwoodie et al. (2015), the quantitative trend is relatively consistent across the cases. The model presented in this paper gives the median level of direct O&M costs in most of the reference cases (Figure 4), regardless of the changes in vessel or technician. However, the new model generates the highest cost level within the higher failure case. By comparing to the other models, this highest cost is probably due to the probabilistic failure rates applied on each wind turbine component under various wind speeds. The cost performance in Figure 4 also indicates, in the aggregate, that these model results are placed in the range of other results.

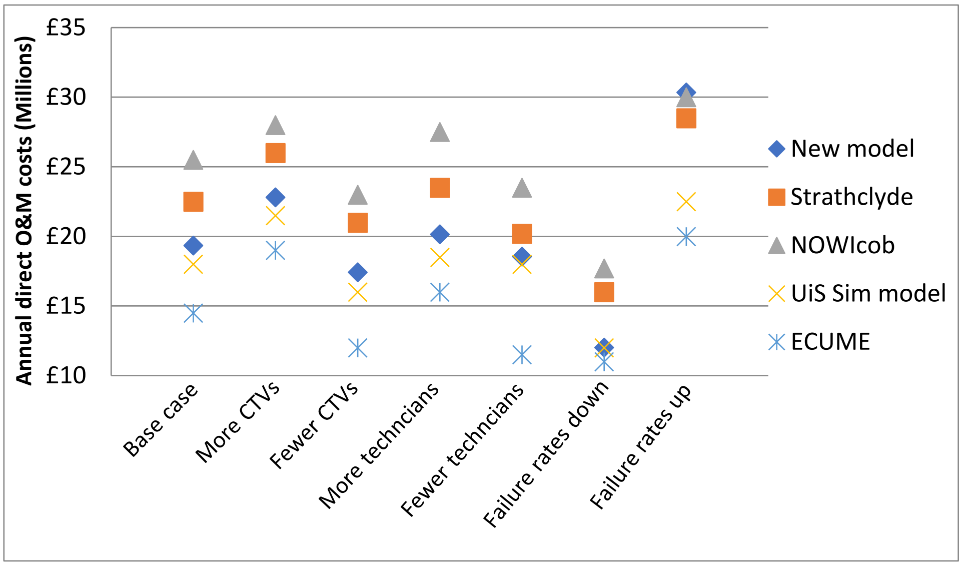

Figure 4. Annual direct O&M cost of the models in the reference cases.

5.3. A Sample Case Study

In order to evaluate the proficiency of the optimisation model, the data of the Rampion offshore wind farm is used as an example. The Rampion offshore wind farm is off the South Coast of the UK, and it is one of the new 'round 3' offshore wind sites designated by the UK government. As the data shown in Table 5, 116 wind turbines have been installed in the farm, which are specified technically by the rated capacity of 3.45MW and the rated wind speed of 12.5 m/s. The average distance from the maintenance base to the OWF is 16.9 km. The mean wind speed over the last 10 years is 9.81 m/s.

Table 5. Offshore wind farm & turbine inputs.

Parameter	Value	Unit
Number of turbines	116	turbine
Generation capacity	3.45	MW
Cut-in wind speed	3	m/s
Rated wind speed	12.5	m/s
Cut-out wind speed	25	m/s
Distance to port	16.9	km
Water depth	19–39	m
Mean wind speed	9.81	m/s

In this study, the model was coded in the programming of A Mathematical Programming Language (AMPL) and then solved by the solver Gurobi on a laptop with CPU Core i5 2.4 GHz and 8 GB RAM. The optimal solutions with respect to different input parameter data were acquired by the solver of Gurobi within a reasonable computation time. With regard to the expected maintenance workload based on the wind-speed-dependent failure rates, the model estimates the number of hours for each transportation type and technicians in different maintenance categories on the range of wind turbine components. The total cost is minimised by the developed model with the maintenance demand.

All the involved costs, including transportation, labour, fuel, repair material and downtime costs, are taken into account in the experimentation. Fixed and charter costs occur in hiring a required transport. Fuel cost covers the expenditures of fuel consumption per m^3. Labour cost is assumed to be the annual salary of full-time or part-time technicians. The downtime cost is calculated by the energy potentially generated during the breakdown and the wholesale electricity price. The unit cost per MWh of both preventative and corrective maintenance is estimated, as the major outcome, with all the above types of costs and the amount of energy produced. The model is also able to determine the minimum O&M cost with the best transport selection; it assists decision-makers in making a decision on the most suitable maintenance plan. A sensitivity analysis considering different scenarios, namely 50% higher mean failure rates and 50% lower mean failure rates, is given in Table 6.

As the solution of the sample case shows in Table 6, three CTVs should be scheduled to meet the annual maintenance demand; eight chartering periods of FSV and five chartering periods of JUV are required. No helicopter is scheduled to execute maintenance service, although it was an optional maintenance transport. This could result from the relatively higher costs and restricted compatibility to maintenance categories on this transportation mode. From the row "Number of technicians", it can be seen that under the normal failure rate, four full-time and two part-time technicians are hired on CTVs to meet the maintenance labour demand. The full-time technicians on FSV or JUV can be deployed to work temporarily on CTVs. More part-time technicians will be used than full-time on FSVs and JUVs since major repair and replacement do not occur throughout the whole year.

Table 6. Comparison of sample case results with higher and lower failure rates.

	Sample Case	50% Higher Failure Rates	50% Lower Failure Rates
Maintenance working hours required			
Crew transfer vessel	6479	8677	2892
Field support vessel	632	996	325
Jack-up vessel	793	1440	418
Helicopter	0	0	0
Number of transport charter periods required			
Crew transfer vessel (charter period: 1 year)	3	5	2
Field support vessel (charter period: 1 week)	8	12	4
Jack-up vessel (charter period: 2 weeks)	5	9	3
Helicopter (charter period: 3 weeks)	0	0	0
Number of technicians required			
F/T Crew transfer vessel	4	7	3
P/T Crew transfer vessel	2	3	1
F/T Field support vessel	1	2	0
P/T Field support vessel	4	3	5
F/T Jack-up vessel	8	15	1
P/T Jack-up vessel	13	7	20
F/T Helicopter	0	0	0
P/T Helicopter	0	0	0
Estimated costs			
Preventative maintenance cost per MWh (£)	6.70	6.70	6.70
Corrective maintenance cost per MWh (£)	19.42	31.95	9.23
Total maintenance cost per MWh (£)	26.12	38.65	15.93

In the 50% higher failure rates scenario, as shown in Table 6, the number of CTVs demonstrates an increase by two; and longer charter leases of FSV and JUV are also requested to satisfy the increased maintenance demands. Three additional full-time technicians and one additional part-time technician on CTVs are needed to match the maintenance workload with a 50% increase in failure rates. On the field support vessel, one more full-time technician replaces one part-time technician in order to provide more service time. A significant change is shown in the number of technicians on the Jack-up vessel; seven extra full-time persons are employed with a reduction of six part-time technicians. By considering 50% lower failure rates, more part-time technicians are hired on all types of transport because part-time employees are more cost-effective to satisfy the decreased maintenance demand.

The cost distribution is investigated for the three scenarios. According to the average results of the scenarios, transport charter cost contributes 51% of the total maintenance cost (shown in Figure 5). Loss of energy production during downtime gives 23%, and transport fixed cost occupies 15%. If the chartering period of FSV and JUV is extended to two months or longer per lease, then the total transport fixed cost could be reduced. Labour cost presents a small percentage (3%), and transportation fuel is less than 1% of the total cost.

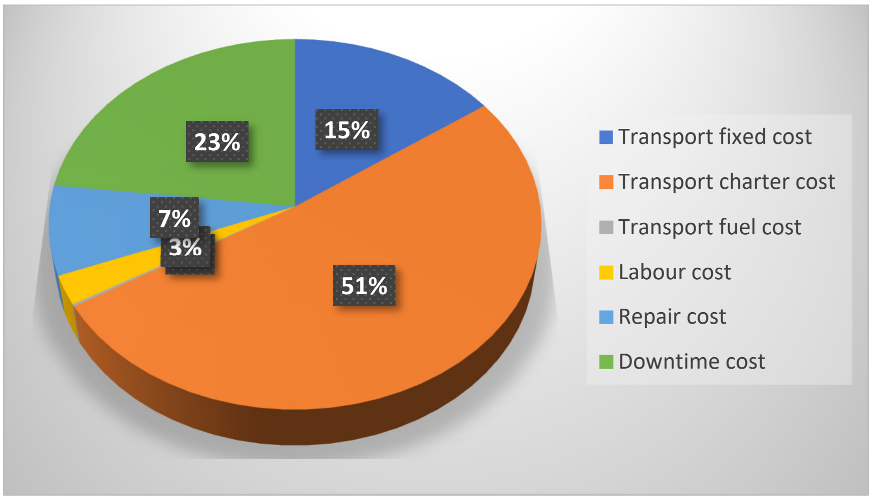

Figure 5. Distribution of each cost element in offshore wind maintenance.

6. Conclusions

Although offshore wind technology has been developed rapidly during the last decades, there are a limited number of optimisation models available to support O&M planning activities. This paper proposes a decision-making model to assist offshore wind project developers in planning cost-effective O&M decisions. The optimisation model aims to minimise the total cost of O&M activities, including transport fixed cost, transport charter cost, transport fuel cost, labour cost, repair cost and downtime cost, in offshore wind maintenance during a given period of time.

Five categories of maintenance and key components of wind turbines are considered in the developed model in order to produce realistic results. A transport type may be used to undertake maintenance activities on multiple maintenance categories. For example, jack-up vessels are compatible with carrying out major repairs and major replacements. Technicians may also be used flexibly between different transport types to execute different maintenance categories. For instance, the technicians on jack-up vessels or field support vessels are entitled to work on crew transfer vessels for smaller repairs. Wind-speed-dependent failure rates on different turbine components were considered in the optimisation model. The model takes into account the wind speed probabilities in a particular OWF, so it is able to supply a practical solution. By using the model solution, the effect of seasonal changes on wind turbine operation can be accounted for.

The results obtained from the optimisation model are able to contribute effectively to the planning of O&M resources and activities in advance to meet the necessary maintenance demand. Both the required transportation and labour will be used effectively to improve the performance cost. The revenue loss during downtime is regarded as another key element in O&M cost. According to the sensitivity analysis, the experimental results considering the sample OWF imply that the reliability of wind turbine components has an immediate effect on maintenance costs. Therefore, this proposed model can support offshore wind stakeholders in understanding the strategic resource requirement associated with the maintenance of an OWF.

Both transport and labour are utilised effectively in the optimal solutions. However, the utilisation could potentially be included as further objectives in the optimisation model rather than considering cost-related objectives only. A balance between service efficiency and cost-effectiveness could be achieved with a multi-objective optimisation model. The effect of sea state, such as wind speed, is one of the most significant factors causing uncertainty in the maintenance planning of OWFs. Weather forecast on a short timescale could be accurate, but it is not sufficient to support the strategic plan of offshore wind maintenance. Any sea state changes may result in a significantly different solution from that predicted by the mean value.

The Weibull distribution was applied for the weather forecast based on historical weather data in the OWF location. It is suggested to fit multiple weather scenarios into this optimisation model and different occurrence probabilities in each scenario. Alternatively, other stochastic modelling techniques might be considered for weather simulation, such as a Markov chain, and integrated into the decision-making model. Different stochastic models require different data inputs. Hence, this model can be deployed in a wider range of realistic cases with various data availability. Finally, the correlation of preventive maintenance with component failures can be investigated and included in the model as an extra parameter in future research.

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Nomenclature or Abbreviations

Nomenclatures:	
O&M	Operation and maintenance
OWF	Offshore wind farm
CTV	Crew transfer vessel
FSV	Field support vessel
JUV	Jack-up vessel
HEL	Helicopter
Sets:	
$i \in I$	Set of maintenance categories
$j \in J$	Set of wind turbine components
$k \in K$	Set of transport types
$w \in W$	Set of wind speeds
Parameters:	
C_k^{fixed}	Fixed cost of transport type *k* in a charter period
$C_k^{charter}$	Charter cost of transport type *k* per day
C_k^{fuel}	Fuel cost per m^3 of transport type *k*
$C_k^{labourFT}$	Labour cost of a full-time technician working on transport type *k*
$C_k^{labourPT}$	Labour cost of a part-time technician working on transport type *k*
C_{ij}^{repair}	Repair material cost of maintenance category *i* on component *j*
C^{down}	Expected downtime cost per MWh
D	Distance to maintenance base port
N	Number of wind turbines
Q_{ij}	Number of technicians required for maintenance category *i* on component *j*
F_{ij}	Mean failure rate of category *i* on component *j*
T_k^{travel}	Travel time of transport *k* from the base port to OWF
T_{ij}^{repair}	Expected repair time of category *i* on component *j*
T_{kw}^{wait}	Expected waiting time of transport *k* under wind speed *w*
S_k	Speed for transport *k*
O_k	Fuel consumption ($m^3 per\ hour$) of transport *k*

$H_k^{transport}$	Total hours per chartering period of transport *k*
$H_k^{labourFT}$	Total hours of a full-time technician on transport *k*
$H_k^{labourPT}$	Total hours of a part-time technician on transport *k*
L_k^{shift}	Working hours of a shift on transport *k*
$B_{ik}^{compatible}$	=1, if transport *k* is compatible with category *i* =0, otherwise
$B_{kw}^{deployable}$	=1, if transport *k* is deployable under wind speed *w* =0, otherwise
$Prob_w^{wind}$	Probability of wind speed *w*
$Prob_{w,ij}^{wind\|fail}$	Probability of wind speed *w*, given a failure occurred to category *i* on component *j*
$\lambda_{ij,w}^{fail\|wind}$	Probability of failure of category *i* on component *j* under wind speed *w*
G_w^{avail}	Power generated per hour under wind speed *w*
Cap^{rated}	Rated capacity of a wind turbine
A	Swept area of a wind turbine
ρ	Air density
Coe^p	Coefficient of the power of a wind turbine
WS_w	Value of wind speed *w*
WS^{in}	Cut-in wind speed
WS^{out}	Cut-out wind speed
WS^{rated}	Rated wind speed
Decision variables:	
x_k^{α}	Number of charter periods of transport *k* required
x_{kw}^{β}	Number of charter periods of transport *k* required under wind speed *w*
x_{ikw}^{γ}	Number of charter periods of transport *k* required for category *i* under wind speed *w*
x_{ijkw}^{δ}	Number of charter periods of transport *k* required for category *i* on component *j* under wind speed *w*
$y_k^{FT,\alpha}$	Number of full-time technicians on transport *k*
$y_{kw}^{FT,\beta}$	Number of full-time technicians on transport *k* under wind speed *w*
$y_{ikw}^{FT,\gamma}$	Number of full-time technicians on transport *k* for category *i* under wind speed *w*
$y_{ijkw}^{FT,\delta}$	Number of full-time technicians on transport *k* for category *i* on component *j* under wind speed *w*
$y_k^{PT,\alpha}$	Number of part-time technicians on transport *k*
$y_{kw}^{PT,\beta}$	Number of part-time technicians on transport *k* under wind speed *w*
$y_{ikw}^{PT,\gamma}$	Number of part-time technicians on transport *k* for category *i* under wind speed *w*
$y_{ijkw}^{PT,\delta}$	Number of part-time technicians on transport *k* for category *i* on component *j* under wind speed *w*
z_{ijkw}	= 1, if transport *k* is selected for category *i* on component *j* under wind speed *w* = 0, otherwise

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