THE INFLUENCE OF MULTIPLE WORKING SHIFTS FOR OFFSHORE WIND FARM O&M ACTIVITIES – STRATHOW-OM TOOL

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SUMMARY

Challenging climate conditions limit the operability and accessibility of the maintenance vessels significantly; therefore, the turbine downtime due to vessel inaccessibility becomes dominant compared to the downtime due to component supply and actual repair. In the current operational practice, day-to-day operations are performed in single shift basis; however, considering two working shifts (day and night) can be the solution towards minimised downtime. In this context, the focus of this research is the investigation of operational and financial benefits that multiple working shifts can bring to the operating offshore farms. The operational simulations are performed by the offshore wind operational expenditure and logistics optimisation tool StrathOW-OM, which is developed by the University of Strathclyde and commercial partner organisations. StrathOW-OM examines climate parameters in the offshore wind farm location, size and operational characteristics of the maintenance fleet, and failure rates of the turbine components. The operational simulations are performed through multiple scenarios in order to identify the most cost efficient solution.

1. INTRODUCTION

1.1 OFFSHORE WIND O&M

It is expected that the vessel fleet associated with the offshore wind industry needs to increase by 500% by 2020 to meet the planned demand [1]. As offshore wind farms move further offshore, Operation and Maintenance (O&M) access by conventional Crew Transfer Vessels (CTVs) becomes more difficult and time consuming. Although, there are alternative methods such as offshore access vessel and mothership concepts, these methods are not mature enough to compete with the offshore wind access issues. Moreover, including additional vessels in the O&M fleet increases the costs significantly, considering the fact that the vessel charter costs have highest share in the total O&M cost [2].

According to a report prepared by WindPower Offshore [3], the proportion of the CTVs to the number of vessels in the entire offshore wind market is 40.6%. Despite the dominance of the CTVs, there is no regulation specifically for offshore wind farm service vessels [4]. Technicians performing offshore O&M are classed as passengers, and therefore if there are more than 12 technicians on-board, this specific vessel is classified as a passenger vessel, which introduces extensive safety legislation and decrease operational flexibility. Furthermore, weather conditions restrict access of the CTVs; larger vessel may have better operational capabilities but charter rates escalate quickly.

Different models have been developed to analyse offshore wind O&M activities. Bussel and Bierbooms [5] investigated inflatable boats, special offshore access systems and helicopters for O&M activities within the DOWEC project. The BMT MWCOST tool considers the significant wave height observations as a limitation for the vessel access [6]. The O2M tool takes the wave height values into account and performs time domain Monte simulations [7]. The ECN O&M Tool, which analyses O&M costs and downtime, is one of the most comprehensive tools available in the offshore wind O&M market [8-10]. At the later stages, the Operation and Maintenance Cost Estimator has been developed by ECN to predict future O&M costs [11]. Although the major aspects are taken into account, there are limitations with the current portfolio of developed models. Offshore access related operations are generally overly simplified or modelled in a crude way. Furthermore, additional climate parameters (i.e. wave period and duration daylight) are required to be modelled in order to present the operational limitations in a more comprehensive manner.

1.2 SCOPE OF THE STUDY

This study investigates the influence of multiple working shifts for the offshore wind farm O&M campaigns on projected operational performance, cost and revenues. This is achieved by using a detailed lifetime operational expenditure (OPEX) and revenue model, StrathOW-OM Tool, with a baseline wind farm in the North Sea. The operational simulations are performed through multiple O&M CTV configurations in order to identify the most cost efficient solution. By keeping all the other inputs; climate, wind farm configuration, and wind turbine performance inputs consistent, it is possible to quantify the influence of the CTV usage on the overall performance of the turbines. For the operational phase, there is a complex relationship between the CTV usage and OPEX. The developed methodology brings new insights into this relationship and potential improvements in the usage of current O&M resources.

2. METHODOLOGY

In this study, the developed methodology is divided into three main sections: Inputs, Simulations, and Outputs (Figure 1). The Inputs section is the stage that the information about a case is defined and this specific information is delivered to the Simulations section. Thereafter, the specific information is processed, analysed within specific sub-sections and the operational simulations are performed. The results of the operational simulations are averaged in the Outputs section and final results are presented. In the following sections details are provided related to each section and sub-section.

2.1 INPUTS

The climate inputs in the developed methodology comprise of historical wind speed, wave height, wave period observations, probability of good visibility, and duration of daylight values collected from a specific location. The offshore vessel operations and O&M activities are influenced by wind speed, wave height, wave period, visibility and duration of daylight observations, whilst the power productivity of the specified offshore wind farm is only influenced by the wind speed observations. The duration of daylight algorithm is adopted from [12].

The vessel specifications and the O&M fleet configuration comprise of CTV, jack-up vessel, and helicopter specific inputs (Table 1). The *Vessel type* input for CTVs presents the hull type of the defined CTV, which is either monohull or catamaran. The CTV inputs 2-11 display the generic characteristics of the CTVs. The *Maximum visit per CTV* is the maximum number of operations that can be done by a CTV in a single shift to provide CTV sufficient time to react to emergency situations. The *Inter transit time* is the time required for the CTVs to travel from a turbine to another turbine. The *Time start to work* is the time spent between the time that the technicians are transferred from a CTV to a turbine and the time that the technicians start actual O&M task. The time to carry all the equipment from the CTV into the nacelle can be considered within the *Time start to work*. The *Minimum working limit* has to be defined for making a working shift acceptable and cost-effective.

The helicopter operations are also considered in the methodology in addition to conventional access systems. The *Contract hour* is the certain number of annual flying hours, for which the helicopter is chartered. The helicopter inputs 2-5 display the generic characteristics of the helicopter.

In the case of blade, generator or tower failures, CTVs or helicopter cannot perform the replacement of damaged components; therefore, a jack-up vessel is chartered. In the maritime industry, voyage charter (spot market), time charter and bareboat charter are the commonly used three types of contractual arrangements. In the developed methodology, voyage charter is considered due to the difficulty to arrange crew, provide provisions and complete administrative jobs for short-term; therefore, all the jack-up related costs are considered to be included in the daily charter rate.

The *Mobilisation time* for the jack-up operations is defined through selecting a random value from a triangular distribution, for which the lower limit, mode and upper limit are indicated by the optimistic, expected, and pessimistic mobilisation time values, respectively. The *Batch repair threshold* is the number of major components that has to fail before chartering the jack-up vessel. The jack-up vessel inputs 7-15 display the generic characteristics of the jack-up vessel.

The wind farm/turbine inputs are the number of wind turbines, the power production values for associated wind speeds, and the time dependent failure rates of the turbine components. The major cost aspects such as vessel charter, original equipment manufacturer (OEM), technician and fuel are considered in the methodology. In addition, the electricity price is modelled to calculate the total revenue and the total financial loss.

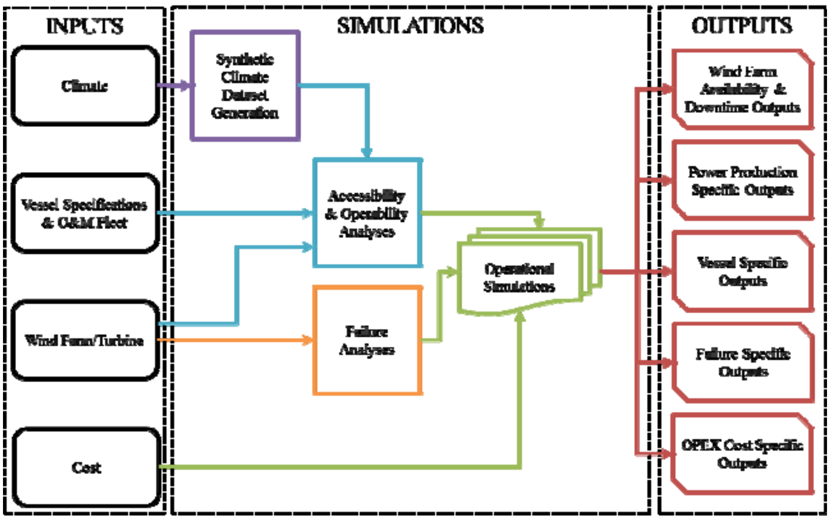

Figure 1: Developed methodology

Table 1: Vessel specifications and fleet configuration inputs

Access Type					
Crew Transfer Vessel		Helicopter		Jack-up Vessel	
1	Vessel type	1	Contract hour	1	Charter type
2	Length	2	Operational speed	2	Charter length
3	Breadth	3	Fuel consumption	3	Mobilisation time (opt.)
4	Draught	4	Max. op. wave height	4	Mobilisation time (exp.)
5	Displacement	5	Max. op. wind speed	5	Mobilisation time (pes.)
6	Installed power			6	Batch repair threshold
7	Technician capacity			7	Component capacity
8	Operational speed			8	Port re-supply time
9	Fuel consumption			9	Jack-up time
10	Max. op. wave height			10	Blade removal time
11	Max. op. wind speed			11	Operational speed
12	Shift start			12	Fuel consumption
13	Maximum visit per CTV			13	Max. op. wave height
14	Inter transit time			14	Max. op. wind speed
15	Time to start work			15	Lifting wind speed limit
16	Minimum working limit				

2.2 SIMULATIONS

2.2 (a) Synthetic Climate Dataset Generation

It is rare that the climate data will present exactly the same track in the following years; therefore, it is important to generate alternative climate dataset by also preserving the characteristics of the original dataset. The developed model has the capability of generating synthetic wind speed, significant wave height and wave period time series using a Multivariate Auto-Regressive (MAR) model, developed from the methodology in [13, 14]. The determination of MAR coefficients and model generation is implemented using the arfit algorithm in MATLAB [15]. In order to preserve the variability in performance driven by climate, a unique synthetic time series is generated for each simulation. By using the described methodology the key characteristics of mean and variance as well as annual distribution, access window duration periods and inter-time step correlation are preserved. In addition, correlation between different climate parameters are preserved.

2.2 (b) Accessibility & Operability Analyses

CTVs operate in waves; through analysing wind speed and significant wave height values, it is possible to identify the time-steps/days in which the CTVs can operate or stay in the specified port. In the developed methodology, the transit time delays due to speed reduction under different climate conditions are considered by also analysing the wave period values. In this context, accessibility and operability analyses are constituted from 5 sequential steps;

- Calculation of total calm water resistance
- Calculation of additional wave resistance
- Calculation of total resistance
- Calculation of speed loss in wavy sea
- Calculation of transit time

The total calm water resistance $R_{T\text{-}Calm}$ of the CTVs can be calculated from the Equation 1 and Equation 2;

$$P_E = P_B / \eta_T \qquad \text{Equation 1}$$
$$R_{T\text{-}Calm} = P_E / V \qquad \text{Equation 2}$$

where P_B is the break power; P_E is the effective power; η_T is the total efficiency of the vessel; and V is the vessel speed at maximum continuous power. In the Equations above, effective power is the necessary power to move the vessel through water, and break power is the power output of the engine without power loss caused by gears, transmissions or friction force.

In heavy seas, waves cause additional resistance on the vessel hull. The most accurate method to calculate additional resistance due to waves is model testing; alternatively, Jinkine and Ferdinande [16] developed an empirical formulation for predicting the added resistance for fast cargo ships in head seas. The dimensional added resistance is related to the non-dimensional added resistance coefficient by Equation 3,

$$R_{AW} = \sigma_{AW} (\rho g \zeta^2 B^2 / L) \qquad \text{Equation 3}$$

where R_{AW} is non-dimensional added resistant coefficient, σ_{AW} is non-dimensional added resistant coefficient, and ζ is wave amplitude; ρ is density of water, g is acceleration due to gravity, B breadth of CTV, and L is length of CTV. The total resistance of the vessel, R_T is the summation of calm water resistance and added resistance due to waves in the ocean (Equation 4).

$$R_T = R_{AW} + R_{T\text{-}Calm} \qquad \text{Equation 4}$$

While a CTV is traveling in a wavy sea, skipper can keep the power constant and decrease the speed or keep the speed constant and increase the power. In this study the power and thrust of the CTVs will be kept constant and speed will change with the influence of added resistance.

In order to calculate the speed loss in each time-step under the condition of constant power and thrust, Equation 5 and Equation 6 derived by Berlekom, et al. [17] and Berlekom [18] can be utilised.

$\Delta V_i/V_0=\sqrt{(1+ R_{AWi/} R_{Ti})}$ Equation 5

$\Delta V_{Ai}= V_0 - \Delta V_i$ Equation 6

where R_{AWi} is the added resistance at time-step i; R_{Ti} the total resistance at time-step i, V_0 is the operational speed of CTV, ΔV_i is the speed loss at time-step i, ΔV_{Ai} is the achievable speed at time-step i.

Transit time is calculated through adding the individual distances that are logged in each time-step, which are the multiplication of achievable speed at time-step i and time step interval (Equation 7). When the summation of these distances become equal to the total distance between the O&M port and the offshore wind farm, it is accepted that the CTV has approached to the wind farm site (Equation 8).

$Distance_i = Time\ Step\ Interval\ x\ V_{Ai}$ Equation 7

$Total\ Distance = \sum Distance_i$ Equation 8

2.2 (c) Failure Analyses

The wind turbine system failure process is implemented using the methodology developed in [19]. The wind turbine is characterised as a series of subsystems that can each exist in a discrete state during each simulation time-step. The probability of shifting states is governed by the component reliability, which is the probability that the component performs satisfactorily for the specified time interval t. In this context, the failure rates $f(t)$, which are determined from observed annual failure rates in operational history and expert judgement, are utilised to calculate the reliability of the turbine components. Time dependent hazard rates provide flexibility to investigate the change of reliability throughout the simulated life time. At each time-step, a uniformly distributed random number, R, in the interval 0 to 1 is generated and then employed to determine if a failure has occurred. If the generated random number is higher than the reliability value of the component at that particular time step, the component fails, otherwise continues functioning.

Each failure is simulated independently for each subsystem. When a failure occurs, an associated O&M task is undertaken based on the associated vessel, cost and technicians requirements. O&M tasks are classified as either preventive maintenance or corrective maintenance; condition based maintenance is not considered directly.

The O&M tasks taking longer than the operating shift are automatically split over shifts. The repair time required at the end of a shift is recorded and updated for the beginning of next shift. Minor failures are assumed cumulative, larger failure types can be specified as cumulative or only possible in single visit. Single visit repairs occur only when a sufficient window is observed although vessels are chartered as soon as the fault occurs for the duration of the downtime.

2.2 (d) Operational Simulations

The simulations are performed through synthesizing all processed climate, failure and operational information. At the beginning of each simulated working shift, any failure that has occurred is assigned to the specified turbine subsystem. In order to perform repair actions, available resources and accessibility are considered. Working hours are limited by a specified shift duration to represent current operational practices. However, climate parameters may not allow vessels to leave the port or transport technicians to wind farm within specified shift or allow only a limited period in the shift. Therefore, the maximum weather window is calculated for each shift in order to identify the maximum period that the technicians can work, which is then used to determine O&M carried out. Repair is then simulated based on the climate time series. If a turbine is in a failed state it will return to a working state when sufficient access time has been observed or when a series of repair actions have been performed corresponding to a completed O&M action.

It is aimed to sustain the productivity at the highest level; therefore the capability of completing the O&M tasks in a single working shift is the most important consideration in the CTV allocation (Figure 2). It is also targeted to utilise optimum number of vessels in order to minimise the fuel cost; therefore it is prioritised to utilise a CTV which is already in the offshore wind farm. Due to the fact that none of the CTVs will be allocated at the beginning of the working shift, having maximum number of working hours is the consideration while allocating a CTV at the beginning of the working shift. In this context, when the CTV with maximum number of working hours is allocated at the beginning of the working shift, the same CTV will be allocated for the subsequent repairs until it runs out technicians or the number of visits becomes equal to the maximum number of visits that can be done by the CTV.

In the simulation logic, helicopter associated O&M tasks are simulated after the main CTV O&M tasks; however, the technician allocation and repair processes are simulated concurrently to other O&M tasks. In a single shift a helicopter O&M task can be carried out only on the turbines that have not been visited by the CTVs. If there are remaining corrective repairs on the turbines that have not been visited (either because of a large number of turbines or because the helicopter has higher accessibility criteria) then the helicopter is utilised for these repairs subject to having remaining flight hours in the year and the site being accessible. Preventive maintenance will only be performed using the helicopter if the number of available flight hours in the year is equal to the number of remaining work hours in the year. Helicopter repairs are limited by daylight hours, visibility, wave height and wind speed.

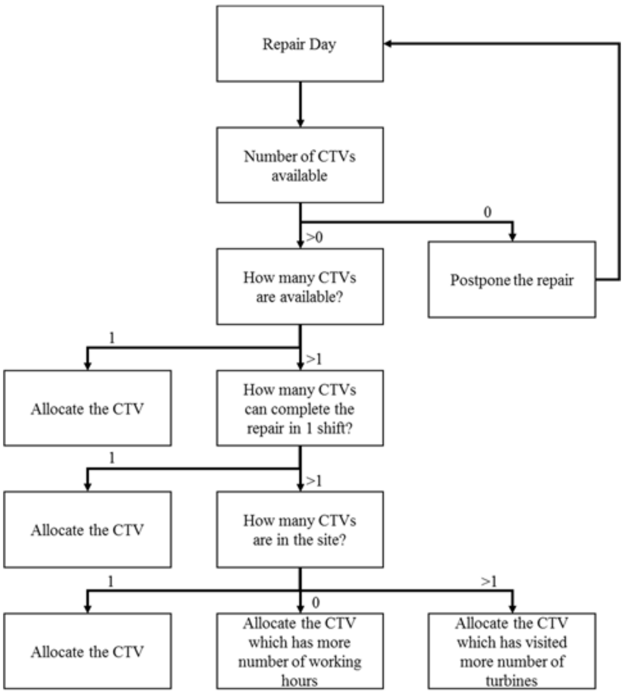

Figure 2: CTV allocation

Jack-up repairs are performed sequentially as soon as a failure of this category occurs. After the first failure is identified, a jack-up vessel is mobilised. Once the mobilisation time is completed, the repairs can be performed subject to wind speed and wave height conditions. The jack-up operation is determined by wind speed at sea level and wave height, whilst the main repair operation is performed subject to wind speed at hub level. The jack-up vessel remains available for the duration of the charter period and repair work and/or movement between wind turbines or to port to re-supply is only carried out when climate conditions allow. Any unfinished tasks at the end of charter period remain incomplete until another vessel is mobilised.

2.3 OUTPUTS

The methodology provides major outputs such as availability, power production, vessel utilisation, mean time to repair values, and cost attributes in order to support the decision making process. In this study, the focus is the CTV associated operations; therefore the key CTV outputs such as CTV utilisation and CTV travels are presented.

3. CASE STUDY

In the operational simulations, an offshore wind farm, which consists of 150 3.6 MW turbines is considered. The distance between the O&M port and the offshore site is 35 nmiles. Table 2, which the names of the inputs refer to Table 1, shows the O&M fleet associated inputs. In addition, the major cost inputs are listed in Table 3.

In the case study, different CTV fleet configurations are simulated. By keeping all other inputs; wind farm configuration, wind turbine performance, helicopter and jack-up vessel inputs consistent, it is possible to quantify the influence of multiple working shifts on overall cost of energy calculations. In order to distinguish day and night shifts, CTV fleets are classed *Day Shift* and *Night Shift*. The size of the CTVs in the *Day Shift* varies between 1 and 10. For the *Night Shift*, the maximum number of CTV that can be utilised cannot be more (can be less) than the CTV fleet defined for the *Day Shift*. For instance, if the size of the CTV fleet in the *Day Shift* is 6, the number of CTVs can be allocated during the *Night Shift* can be 6 or less within this configuration. The technician pool for the O&M activities increases proportional to the CTV fleet size. It is envisaged that night working shift does not require additional CTVs, but the technician pool should be increased.

Table 2: Vessel spec. & fleet configuration inputs

Access Type					
CTV		Helicopter		Jack-up Vessel	
1	Catamaran	1	500 hours	1	Voyage charter
2	18 m	2	50 knots	2	2 weeks
3	6 m	3	0.4 m^3/h	3	7 days
4	1.8 m	4	4 m	4	60 days
5	35 tons	5	18 m/s	5	120 days
6	1118 kW			6	1 component
7	12			7	3 components
8	24 knots			8	24 hours
9	0.24 m^3/h			9	3 hours
10	1.5 m			10	8 hours
11	25 m/s			11	11 knots
12	08:00			12	0.55 m^3/h
13	4 turbines			13	2.8 m
14	10 minutes			14	36.1 m/s
15	30 minutes			15	15.3 m/s
16	2 hours				

Table 3: Cost inputs

No	Input Name	Unit
1	Electricity price	*140 £/MWh*
2	CTV charter	*4000 £/day*
3	CTV fuel	*450 £/mt*
4	CTV technician	*60,000 £/year*
5	CTV fixed	*50,000 £/year/CTV*
6	Helicopter charter	*3000 £/hour*
7	Helicopter fuel	*1200 £/mt*
8	Helicopter technician	*80,000 £/year*
9	Jack-up vessel charter	*100,000 £/day*
10	Jack-up vessel mobilisation	*800,000 £*
11	Jack-up vessel fuel	*300 £/mt*
12	Jack-up vessel technician	*100,000 £/year*
13	Preventive maintenance	*10,000 £/turbine/year*
14	Port operations	*800,000 £/year*
15	Insurance	*5 M£/year*

4. RESULTS

The results of the operational simulations are listed in ascending order according to the total O&M cost/MWh values (Table 4). Total O&M cost/MWh is selected for the final comparison, because it reflects the level of financial benefit (production increase) and loss (cost increase) achieved through considering *Night Shift*. In order to preserve consistency, the *Configuration Number* the figures refers to Table 4. Figure 3 shows the total O&M cost/MWh associated with each configuration. Although the two graphs (top-bottom) show the same aspect, the vertical is limited in the bottom graph in Figure 3 in order to present the cost trends in a clearer way. The total direct O&M cost comprise of charter cost, OEM cost, technician cost, fuel cost, fixed costs, port operations, and wind farm insurance; the total O&M cost comprises of lost revenue and total direct O&M cost.

From the interpretation of Table 4 and Figure 3, it can be seen that considering the *Night Shift* brings considerable advantage towards minimising O&M costs. The lowest O&M cost/MWh (42.6 £/MWh) is identified when 4 and 4 CTVs are utilised in the *Day Shift* and *Night Shift*, respectively. On the contrary, the highest O&M cost/MWh (4240.6 £/MWh) is identified when 1 and 0 CTVs are utilised in the *Day Shift* and *Night Shift*, respectively. Figure 3 also shows that the decrease in the total direct O&M cost results in an increase in the lost revenue. When the resources (the number of CTVs and technicians) are scarce, the costs decreases; however the power production decreases considerable more, which increases the lost revenue (Configurations 58-65). From Table 4, we conclude that those configurations with the greatest cost are more likely to have no night shift technicians. For example, 10 out of the 17 most costly configurations do not have CTV for *Night Shift*. It should also be highlighted that the number of CTVs during *Day Shift* and *Night Shift* is distributed evenly (or close to even) in best configurations such as *4-4* and *5-4,* because the resources are utilised in an optimum manner with minimum redundancy.

The model also outputs the CTV utilisation values. Utilisation is the proportion of time-steps that the CTVs are utilised divided by the total number of time-steps considered in the simulation. Since the simulations are run for 5 years, the total number of time-steps is 43,800 (*5 x 8760 hours*). The average Night Shift utilisation values are higher than the average Day Shift utilisation values; because, the number of CTVs considered during the *Night Shift* is generally lower than the CTVs considered in the *Day Shift*, which increases the average CTV utilisation. In Table 4, it can also been seen that the highest utilisation may not the lead the lowest O&M cost. Eventually, lack of resources may result in high CTV utilisation. On the other hand, if the utilisation is significantly low, the consequence is high total direct O&M cost, which can be compensated by the increase in the power productivity.

In the most favourable configuration, the utilisation (during *Day Shift* and *Night Shift*) of the CTVs 1-4 are 93%, 50%, 41%, 37%, respectively. In this configuration, the CTVs are travelled 4,354 hours, 2,419 hours, 1,992 hours, and 1795 hours, respectively. In the worst favourable configuration, the utilisation (during *Day Shift*) of the CTV 1 is 1.00 and this CTV is travelled 4,934 hours. There is no *Night Shift* in the worst favourable configuration; therefore the utilisation of CTVs during *Night Shift* is set to 0.

Table 4: The list of CTV fleet configurations (from best to worst)

Conf. No	No CTVs Day-Night	Utilisation Day-Night	Cost/MWh (£/MWh)	Conf. No	No CTVs Day-Night	Utilisation Day-Night	Cost/MWh (£/MWh)	Conf. No	No CTVs Day-Night	Utilisation Day-Night	Cost/MWh (£/MWh)
1	*4-4*	*0.56-0.56*	*42.62*	23	*6-1*	*0.56-0.94*	*46.09*	45	*9-2*	*0.36-0.67*	*48.51*
2	*5-4*	*0.48-0.53*	*42.93*	24	*4-2*	*0.67-0.79*	*46.09*	46	*10-1*	*0.36-0.92*	*48.80*
3	*6-5*	*0.41-0.44*	*43.44*	25	*8-4*	*0.35-0.47*	*46.10*	47	*10-10*	*0.25-0.25*	*48.89*
4	*6-6*	*0.39-0.39*	*43.46*	26	*7-2*	*0.44-0.70*	*46.14*	48	*10-8*	*0.26-0.29*	*49.27*
5	*5-5*	*0.46-0.46*	*43.53*	27	*8-8*	*0.30-0.30*	*46.22*	49	*7-0*	*0.59-0.00*	*49.58*
6	*7-6*	*0.35-0.38*	*43.75*	28	*10-6*	*0.27-0.35*	*46.43*	50	*8-0*	*0.52-0.00*	*49.59*
7	*5-3*	*0.52-0.62*	*43.82*	29	*9-6*	*0.29-0.36*	*46.58*	51	*10-9*	*0.25-0.27*	*49.98*
8	*8-7*	*0.31-0.33*	*43.87*	30	*9-3*	*0.34-0.54*	*46.80*	52	*10-0*	*0.42-0.00*	*50.04*
9	*6-3*	*0.46-0.59*	*43.91*	31	*9-5*	*0.31-0.40*	*46.86*	53	*9-0*	*0.47-0.00*	*50.10*
10	*6-4*	*0.43-0.50*	*44.16*	32	*9-4*	*0.32-0.46*	*46.96*	54	*6-0*	*0.67-0.00*	*51.31*
11	*8-5*	*0.33-0.41*	*44.63*	33	*7-1*	*0.49-0.94*	*46.97*	55	*3-2*	*0.79-0.85*	*51.62*
12	*5-2*	*0.57-0.75*	*44.80*	34	*8-1*	*0.44-0.93*	*47.02*	56	*4-1*	*0.77-0.95*	*52.52*
13	*7-4*	*0.39-0.48*	*44.87*	35	*9-7*	*0.29-0.32*	*47.04*	57	*5-0*	*0.79-0.00*	*54.19*
14	*8-2*	*0.40-0.68*	*44.88*	36	*10-3*	*0.31-0.53*	*47.04*	58	*2-2*	*0.94-0.94*	*57.97*
15	*7-5*	*0.37-0.42*	*44.98*	37	*9-1*	*0.39-0.93*	*47.59*	59	*3-1*	*0.92-0.99*	*60.34*
16	*6-2*	*0.50-0.72*	*45.06*	38	*10-4*	*0.30-0.45*	*48.01*	60	*4-0*	*0.92-0.00*	*62.08*
17	*7-7*	*0.34-0.34*	*45.11*	39	*5-1*	*0.65-0.95*	*48.06*	61	*2-1*	*0.98-1.00*	*84.84*
18	*4-3*	*0.60-0.65*	*45.13*	40	*9-9*	*0.27-0.27*	*48.15*	62	*3-0*	*0.98-0.00*	*89.06*
19	*7-3*	*0.41-0.57*	*45.32*	41	*10-7*	*0.26-0.32*	*48.17*	63	*1-1*	*1.00-1.00*	*185.08*
20	*3-3*	*0.71-0.71*	*45.55*	42	*10-2*	*0.33-0.66*	*48.30*	64	*2-0*	*1.00-0.00*	*189.36*
21	*8-3*	*0.37-0.55*	*45.77*	43	*10-5*	*0.28-0.39*	*48.39*	65	*1-0*	*1.00-0.00*	*4240.63*
22	*8-6*	*0.32-0.37*	*45.99*	44	*9-8*	*0.28-0.29*	*48.51*	-	-	-	-

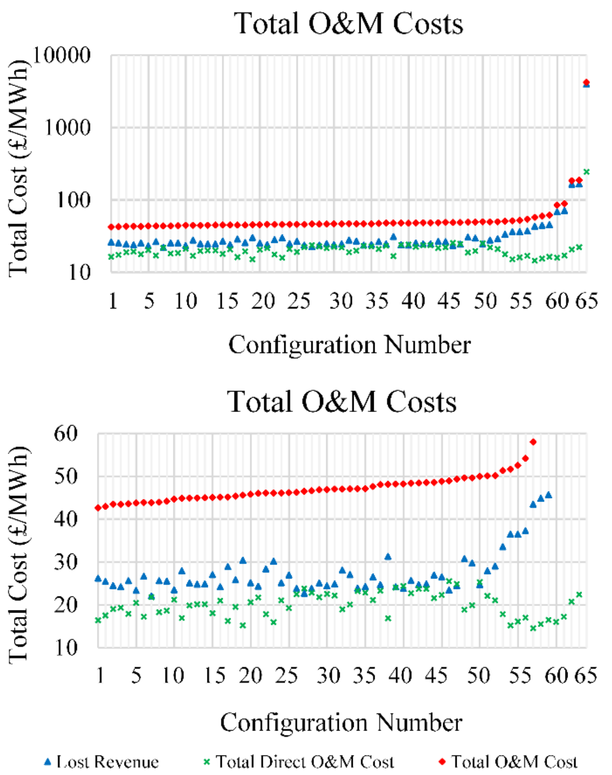

Figure 3: Total O&M costs

The availability and the proportion of completed preventive maintenance are demonstrated in Figure 4. 100% completed preventive maintenance can be achieved by considering a reasonable CTV fleet size (4 or more); however if the CTV fleet becomes relatively small, the CTVs can only be allocated to corrective maintenance activities; therefore, the preventive maintenance completion value declines sharply. In most of the configurations, the availability varies between 80%-85% margin; however, it starts decreasing severely after the configuration 58. This situation shows that there is critical level from the point of CTV fleet size, which is identified 4 CTVs within this case study; if the CTV fleet size becomes smaller than the critical value, the costs and revenue lost increase, availability and the proportion of completed preventive maintenance decrease remarkably.

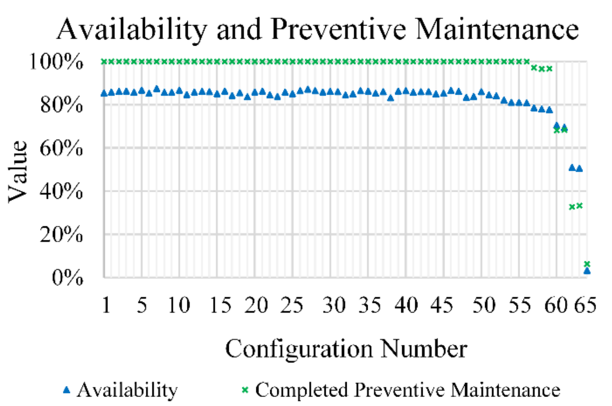

Figure 4: Availability and completed preventive maintenance

5. CONCLUSION

In this research study, the potential benefits of considering night working shift for the offshore wind O&M activities are investigated. Multiple operational simulations are run and optimal solution is identified by ranking the total O&M cost/MWh. Although the operational risks increase by performing O&M activities during night, the achievements cannot be disregarded. It should be highlighted that the current operational practices and regulations strictly (especially in the UK) limit the access to turbines by daylight; however, if the offshore wind industry identifies the financial and operational benefits of the *Night Shift*, advanced technologies can be developed. In addition, when the mothership designs become mature, which provides 24 hour access in a relatively short distance, it is believed that continuous O&M activities will increase the power productivity and decrease the costs.

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