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# A Prognostic Decision Model for Offshore Wind Turbines Maintenance

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## Abstract:

Frequent unscheduled random maintenance activities have significantly increased the operating cost of Offshore Wind Turbines (OWT). These activities account for ~65% of the overall OWT maintenance costs or 23% of the lifetime costs of OWT, equivalent to ~ £26M/yr for a 100MW offshore wind farm. This work performs a quantitative evaluation of the maintenance model suggested by Sinha Y et al (2013) as a means to determine the threshold levels for planning an economical but effective maintenance for OWT. This study suggests that the model put forward provides a comprehensive framework to make maintenance decisions for OWT components by questioning their Availability, Reliability, Safety, Productivity and Availability of Upgrade Technology. Some case studies have been discussed towards the end of this work that validates this model and brings financial benefits. It is expected that practical use of the maintenance decision model, along with relationships developed in this work, would result in planning for economical, effective and efficient OWT maintenance.

**Keywords:** offshore wind turbines, availability, reliability, safety, productivity, upgrade technology, maintenance, gearbox

## 1. Introduction

A decision model for Offshore Wind Turbine (OWT) maintenance was proposed by Sinha et al (2013)<sup>1</sup> in which questions about OWT Availability, Safety, Productivity, Reliability and Availability of Upgrade Technology were asked in order to improve OWT maintenance. That model has been shown in Figure 1 for reference. So, if assemblies and components of OWT were found to be Unavailable, Unsafe, Unproductive, Unreliable or an upgrade technology was found that could improve performance, maintenance decision for OWT will be advised and not otherwise.

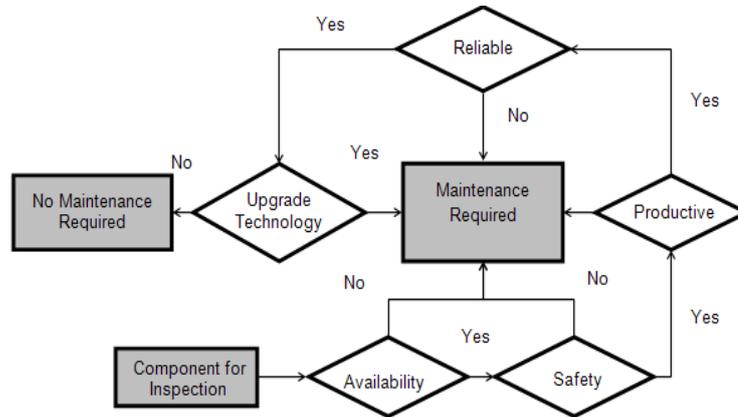


Figure 1 A maintenance decision model to check the need for maintenance implementation (Sinha Y. et al, 2013)

Although a qualitative explanation was provided to justify the utility of the model shown in Figure 1 by Sinha et al (2013), a supportive quantitative evaluation on mathematical grounds was not provided. A quantitative analysis of the model shown in Figure 1 has been shown in this work that establishes mathematical interrelationships between parameters associated with different questions. Answers are in turn used to determine the threshold levels for parameters in the model to plan for an optimal maintenance. Further, this work evaluates the effectiveness and financial gains achieved in some case scenarios when maintenance decisions were based around the above model.

## 2. Mathematical Analysis

### 2.1. Variables

Various parameters used in this work, along with their abbreviations, are defined in Table 1.

Symbol	Comments	Symbol	Comments
A	Availability	T <sub>a</sub>	Time OWT is available for power generation (hr)
A <sub>O</sub>	Original Availability	T <sub>d</sub>	Time OWT is not available due to failure (hr)
A <sub>C</sub>	Changed Availability	T <sub>r</sub>	Time OWT is down due to repair (hr)
C <sub>p</sub>	Cost of generating power (=£135/MWh <sup>2,3</sup> )	T <sub>R</sub>	Turbine Rating
MWh	Megawatts of power generated in one hour	P <sub>p</sub>	Profit Percentage (=25%)
P	Productivity	P <sub>i</sub>	Insurance Premium
P <sub>O</sub>	Original Productivity	N	Number of Wind Turbines in a Wind Farm
P <sub>C</sub>	Changed Productivity	k	Time period when generating partial power
R	Reliability	x	Percentage of actual power generated
R <sub>O</sub>	Original Reliability	λ	Fraction of total time in a year when favourable wind is available
R <sub>C</sub>	Changed Reliability	T <sub>AC</sub>	Time Period for Accident
e	Change in value of Availability	P*	Change in productivity due to maintenance
P* <sub>+</sub>	Positive change in productivity due to maintenance	P* <sub>-</sub>	Negative change in productivity due to maintenance

Table 1 Various Parameters and their abbreviations

## 2.2. Availability

From a maintenance perspective, Availability is defined as “the period of time OWT is available to do its intended work<sup>4n</sup>”. In this work, Availability has been defined as the ratio of time period when OWT was available for doing its work to the total productive time period when it could have generated power. Here, the total productive time for a wind turbine refers to the period of time when wind speed is between cut-in and cut-off limits such that it could operate the wind turbine. Cut-in speed is that wind speed at which an OWT starts to generate power while Cut-off speed is that wind speed above which a wind turbine is shut down, to avoid introducing failures/faults in wind turbine components and the production of negative power, i.e. where wind turbine act like a motor rather than a generator\*. If ‘λ’ is the fraction of time in a year when wind speeds are favourable for operating OWT, and is assumed to be 60% for offshore conditions, an OWT would have favourable operating conditions for 5256 hr (= 0.6\*365\*24 hr) in a year. However, an OWT may or may not be available for power generation due to failure/fault (T<sub>d</sub>) or repair works (T<sub>r</sub>) during this 5256 hrs. So, Availability (A<sub>o</sub>) of OWT operating for T<sub>a</sub> (hr) during this 5256 hr is defined as shown in Equation 1.

$$A_o = \frac{\text{Time OWT is Available for work}}{\text{Total Productive time}} = \frac{T_a}{T_a + T_d + T_r} \quad \text{Equation 1}$$

Where: T<sub>a</sub> = ∑ time in hours when OWT is available for power generation during productive period of a year ; T<sub>d</sub> = ∑ time in hours when OWT is unavailable due to failure/fault observed ; T<sub>r</sub> = ∑ time in hours when OWT is unavailable due to repair works

As an example, if an OWT with rating (T<sub>R</sub>)= 2MW is down for 30 days (1 day = 24 hr, 30\*24 = 720 hr) in the productive time period due to either failure/fault and/or repair, or both, Availability of OWT would reduce from 100% to 91.52% in these 5256 days (Equation 1). If the cost of OWT power generation is taken to be £135/MWh (= C<sub>p</sub>) and supposing that OWT business operates on a profit margin of 25% (= P<sub>p</sub>), the total losses incurred due to this reduced value of A<sub>o</sub> would equal £243,000 (= 135\*30\*24\*2\*1.25) or £168.75/MWh. So, if ten such 2MW OWT were down for 30 days in a wind farm, a total loss of £2.43M would be incurred in that year due to such a failure. A generalised equation to calculate such loss is given in Equation 2.

$$\text{Loss (£)} = 24 \times C_p \times T_R \times N \left(1 + \frac{P_p}{100}\right) \quad \text{Equation 2}$$

Where: x = downtime in days, C<sub>p</sub> = cost of power generation, T<sub>R</sub> = Turbine rating, N = Number of turbines, P<sub>p</sub>= Profit Margin

Equation 2 can be generalised as Equation 3 if ‘λ’ and ‘A<sub>o</sub>’ are known.

$$\text{Loss (£)} = 8760 \lambda C_p T_R N \left(1 - \frac{A_o}{100}\right) \left(1 + \frac{P_p}{100}\right) \quad \text{Equation 3}$$

### 2.2.1. Effect of Maintenance

The value of ‘A<sub>o</sub>’ i.e. Availability of OWT, can be increased if its downtime and/or repair time, or both, can be reduced. Service maintenance is a technique in which failure and faults in a machine are either rectified, as in Failure Based Maintenance, or prevented, as in Preventive Maintenance. However Preventive Maintenance, a method in which a machine is serviced in anticipation of failure (so ‘T<sub>d</sub>’ = 0), supporting high availability of OWT. Hence the use of Preventive Maintenance is beneficial in improving the time an OWT is operational. However if preventive maintenance was to get delayed due to unfavourable offshore weather or lack of inventory/resources, this might introduce a downtime ‘T<sub>d</sub>’, reduce value of ‘A<sub>o</sub>’ and increase financial losses. So any maintenance scheme should aim to:

- Reduce downtime (T<sub>d</sub>) by rectifying failures/faults as soon as reasonably possible
- Reduce time for service maintenance (T<sub>r</sub>) by having prior knowledge of failure and maintenance needs

Hence a prompt and efficiently planned maintenance would reduce financial losses from OWT. However, frequent offshore travel for servicing OWT would add up to make such a strategy overly expensive in the lifetime of OWT. Hence it is important to establish conditions for planning for an efficient but also cost effective maintenance. As maintenance policies and strategies differ with operators, the proposed solution given here offers a generic but useful guide in making any maintenance decision for OWT.

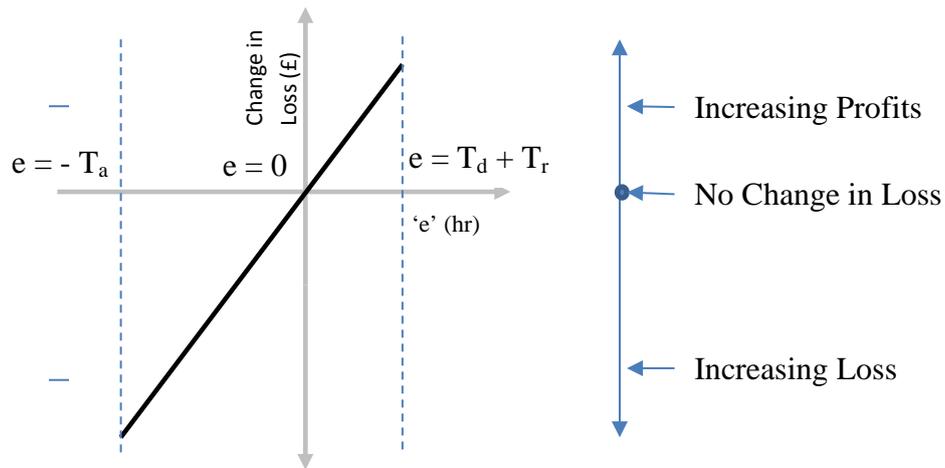
As a result of good and bad maintenance (bad maintenance is when failures and faults in OWT are aggravated due to wrong or hasty maintenance), the value of OWT Availability would change from the Original Availability (A<sub>o</sub>) value to a Changed Availability (A<sub>c</sub>) value. Such a change can be either: (i) *Negative Change*: when the value of A<sub>c</sub> reduces, and (ii) *Positive Change*: when the value of A<sub>c</sub> increases. If ‘-e’ and ‘+e’ represent changes made to ‘T<sub>a</sub>’ due to *Negative Change* and *Positive Change* respectively, the expressions for Changed Availability (A<sub>c</sub>) can be written as shown in Equation 4.

$$A_c = \frac{T_a + e}{T_a + e + T_d + T_r - e} = \frac{T_a}{T_a + T_d + T_r} + \frac{e}{T_a + T_d + T_r} = A_o \left(1 + \frac{e}{T_a}\right) \quad ; \text{ Case of Positive Change}$$

$$A_c = \frac{T_a - e}{T_a - e + T_d + T_r + e} = A_o \left(1 - \frac{e}{T_a}\right) \quad ; \text{ Case of Negative Change} \quad \text{Equation 4}$$

\* Above cut-off speed a wind turbine starts to operate like a fan and takes power away from the grid rather than supplying power to the grid. To avoid this condition a wind turbine is shut down at high wind speeds.

Based on the magnitude of 'e' in the two cases shown in Equation 4, value of  $A_C$  would change. However if the value of 'e' was '0', i.e. there was no maintenance or adverse effects that would have worsened the status of the wind turbine, then there would be no change in the value of  $A_C$  and hence there would be no change in the anticipated losses. As a result there would be no financial benefit of maintenance. However in the event when the value of 'e' equals ' $T_d + T_r$ ', i.e. case where predictive maintenance is able to circumvent downtime and repair time, in that case value of  $A_C$  would equal '1' and would indicate a *Positive Change* in availability. It would also mean that maintenance was able to rectify all faults and so OWT was totally available in the productive time period. Here losses equal to ' $24 (T_d + T_r) C_P T_R N (1 + \frac{P_P}{100})$ ' is avoided due to maintenance. So, if the overall maintenance cost is less than such value, a decision on OWT maintenance would be a wise choice. Similarly, if the value of magnitude of 'e' becomes equal to ' $T_a$ ' in the case of *Negative Change*, ' $A_C = 0$ '. This indicates an event when OWT was totally out of operation when required maintenance was not done or when the effect of external agents was such that OWT failures worsened over time. In such a case maximum revenue losses equal to ' $24 T_a C_P T_R N (1 + \frac{P_P}{100})$ ' would occur and for a wind farm containing 2MW OWT and where 10 such turbines were out of operation, the wind farm would incur a loss of £81,000/day or £3375/hr. A plot of Loss (£) and 'e' has been given in Figure 2 where the conditions for minimum and maximum losses due to failure can be determined at the extreme points of the graph. This can then be used to make maintenance decisions.



**Figure 2 Schematic shows variation in loss with changing availability**

From Figure 2, the financial impact of a positive and negative change made by a maintenance activity can be evaluated. Whereas the operating losses can decrease with increasing positive values of 'e' along the line shown, and vice versa, between the limits ' $T_d + T_r$ ' and ' $-T_a$ ', a general equation of this line is given in Equation 5.

$$\text{slope}(m) = 24 C_P T_R N (1 + \frac{P_P}{100}) ; \text{ Loss } (\text{£}) = 24 C_P T_R N (1 + \frac{P_P}{100}) [e] \quad \text{Equation 5}$$

Using the above equation for slope and line, financial losses at points ' $T_d + T_r$ ' and ' $T_a$ ' can be calculated. These have been given as Equation 6 (a) and Equation 6 (b).

$$\text{Loss}_{Max} (\text{£}) = 24 T_a C_P T_R N (1 + \frac{P_P}{100}) \quad \text{Equation 6 (a)}$$

$$\text{Profit}_{Max} (\text{£}) = 24 (T_d + T_r) C_P T_R N (1 + \frac{P_P}{100}) \quad \text{Equation 6 (b)}$$

So any maintenance activity that makes a significant positive change and whose value of 'e' follows the line from quadrant 3 towards quadrant 1, as shows in Figure 2, would offer financial benefits. However the level of benefit, measured by profit made, should be more than the overall cost of maintenance ( $C_M$ ). If the level of such a change is from ' $e_1$ ' to ' $e_2$ ', where  $e_2 > e_1$  (i.e. assuming maintenance to have positive effect), the profit made by this transition from ' $e_1$ ' to ' $e_2$ ' would equal the value as given in Equation 7. If OWT maintenance costs are to be made economical, then a decision for maintenance should be made when the cost of maintenance ' $C_M$ ' is lower than the profits (P) made by such maintenance.

$$\text{Profit } (P) (\text{£}) = 24 C_P T_R N (1 + \frac{P_P}{100}) [e_2 - e_1] > C_M \quad \text{Equation 7}$$

In order to improve the value of  $A_C$ , and hence the operating profits, the following needs to be done:

- Minimise downtime
  - Anticipate and rectify failures as soon as possible: Use failure prediction techniques
  - Use existing facilities to minimise costs: Use condition monitoring data to predict failure
  - Use guided failure rectification methods: Can reduce time for rectifying failures
  - Early maintenance planning: Repair time and downtime can be reduced
  - Early Rectification of all observed, anticipated and incipient types of failures as soon as possible

- Minimise time to repair failures (/faults)
  - A spares inventory should be maintained to meet immediate demands
  - Manpower, transport vessel and tools/instruments should be readily available
  - Management, administrative and safety procedures (and undertaken time) should be made optimal to reduce delay in maintenance execution
  - New technologies that can simplify OWT servicing should be incorporated in work
  - Use knowledgeable and skilled staff to improve success level of maintenance

### 2.3. Productivity

In this work productivity has been defined as “ratio of actual power generated to the rated power of OWT” and is implied only when wind speeds are in-between cut-in and cut-out limits for OWT, i.e. the productive time period. This can only be measured when it is operational and OWT operates only when wind speeds are in between cut-in and cut-out levels. Here an assumption is made that OWT start to generate rated power at cut-in wind speed (~ 2.5m/s) which in practical scenarios may happens at twice or three times this value (7–12m/s). The cut-out wind speed for OWT is usually ~25m/s. However in the event of a failure, productivity of OWT can be reduced and its capability to generate electrical power would reduce. For example, a 2MW OWT that only generates 1.2MW in favourable wind speed due to failures/faults, would reduce to 60% of its rated value. When an OWT is only capable of converting 60% of wind energy into power (higher than onshore counterpart ~40%)<sup>5</sup>, and favourable wind are available for only 60-70% of the overall time period, incidences of failures and faults further reduces the amount of power that can be generated. As a result, use of early failure diagnosis systems, like failure prediction, and early preventive maintenance can reduce the level of financial losses.

Loss in productivity occurs under two circumstances (i) complete loss in power generation capability by OWT due to a major fault, and (ii) partial loss in power generation capability by OWT due to failures in its assemblies and components. Again, assumptions here are that downtime due to a major fault is  $T_d$  (hr), time for repairs is  $T_r$  (hr) and for ‘ $k_i$ ’ (hr) only ‘ $x_i\%$ ’ of the rated output power is generated. In such circumstances productivity of OWT of ‘ $T_R$ ’ MWh rating operating for ‘ $T$ ’ (hr) ( $= T_a + T_d + T_r$ ) of productive time period would be:

$$P = \frac{\text{Power Generated}}{\text{Rated Power}} = \frac{T_R * T - T_R * \left\{ \sum_{i=1}^n \frac{k_i(x_i)}{100} + T_d + T_r \right\}}{T_R * T} = \left\{ 1 - \frac{\left\{ \sum_{i=1}^n \frac{k_i(x_i)}{100} + T_d + T_r \right\}}{(T_a + T_d + T_r)} \right\} = \left\{ 1 - \frac{\left\{ \sum_{i=1}^n \frac{k_i(x_i)}{100} \right\}}{T_a + T_d + T_r} - \frac{T_d + T_r}{T_a + T_d + T_r} \right\}$$

$$= \left\{ \frac{T_a}{T_a + T_d + T_r} - \frac{\left\{ \sum_{i=1}^n \frac{k_i(x_i)}{100} \right\}}{T_a + T_d + T_r} \right\}$$

$$P = \left\{ A_o - \frac{\left\{ \sum_{i=1}^n \frac{k_i(x_i)}{100} \right\}}{(T_a + T_d + T_r)} \right\} \quad \text{Equation 8}$$

In Equation 8 a relationship between Productivity (P), Availability ( $A_o$ ) and the effect of partial failures is given, from which several deductions can be made. Firstly, productivity is independent of wind turbine rating and secondly, productivity is directly dependent on Availability and partial power loss. This implies that productivity would be high for high values of Availability and would reduce with increasing effect of partial failures. As a result, reducing instances of failures/faults by maintenance would ensure higher productivity from OWT. Suppose that due to maintenance,  $A_o$  changes to  $A_c$ , original failure  $x_i$  initially having an effect for ‘ $k_i$ ’ (hr) is changed to ‘ $k_i^-$ ’ (hr), so Original Productivity ( $P_o$ ) value would change to Changed Productivity ( $P_c$ ), given in Equation 9.

$$P_o = \left\{ A_o - \frac{\left\{ \sum_{i=1}^n \frac{k_i(x_i)}{100} \right\}}{(T_a + T_d + T_r)} \right\}, \text{ and } P_c = \left\{ A_c - \frac{\left\{ \sum_{i=1}^n \frac{k_i^-(x_i)}{100} \right\}}{(T_a + T_d + T_r)} \right\} \quad \text{Equation 9}$$

In order to understand the impact of maintenance, the difference between the above two equations is evaluated, as shown in Equation 10 and Equation 4,

$$\text{Change in Productivity due to Maintenance } (P^*) = P_c - P_o = \left\{ A_c - A_o - \frac{\left\{ \sum_{i=1}^n \frac{x_i(k_i^- - k_i)}{100} \right\}}{(T_a + T_d + T_r)} \right\}$$

$$P^* = \left\{ \frac{\pm e}{T_a + T_d + T_r} - \frac{\left\{ \sum_{i=1}^n \frac{x_i(k_i^- - k_i)}{100} \right\}}{(T_a + T_d + T_r)} \right\} \quad \text{Equation 10}$$

This gives rise to two conditions (i)  $P^*_+$  when maintenance improves availability and rectifies failures and (ii)  $P^*_-$  when external conditions or bad/delayed maintenance introduces more faults and failures in which case productivity would further decrease. These have been shown in Equation 11.

$$P^*_+ = \frac{e - \left\{ \sum_{i=1}^n \frac{x_i(k_i^- - k_i)}{100} \right\}}{(T_a + T_d + T_r)} ; \quad P^*_- = \frac{-e - \left\{ \sum_{i=1}^n \frac{x_i(k_i^- - k_i)}{100} \right\}}{(T_a + T_d + T_r)} \quad \text{Equation 11}$$

In this work only the case when maintenance produces a positive effect on productivity has been considered. Also, since the value of '(k - k<sup>-</sup>)' would be quite small as a result of maintenance, and with  $T = T_a + T_d + T_r = 5256$ , the overall value of  $\left\{ \sum_{i=1}^n \frac{x_i(k_i^- - k_i)}{100(T_a + T_d + T_r)} \right\}$  would be very small and hence this term is neglected for calculations.

The maximum positive and negative values of 'e' was discussed in Section 2.2.1 to be equal to ' $T_d + T_r$ ' and ' $-T_a$ '. Hence a plot of positive change in Productivity with changing value of 'e' has been plotted in Figure 3 between these extreme values. From the plot, value of slope and equation of the line are.

$$\text{slope}(m) = \frac{1}{T_a + T_d + T_r}; \quad P_+^* = \frac{e}{T_a + T_d + T_r}$$

As this is a case of positive change in Productivity, so the plot would show a tendency to increase from ' $-T_a$ ' to ' $T_d + T_r$ ' along the contour of the line shown in Figure 3. This also means that change in productivity is directly proportional to the change introduced in availability due to maintenance ('e'). As a result, minimum and maximum value of changed productivity would be as shown in Equation 12. From Equation 12, if  $\frac{T_d + T_r}{T_a} \ll 1$ , the minimum and maximum values of change made in productivity would be -100% and 0%, i.e. negative change in productivity, a condition that should be avoided. However, if  $\frac{T_d + T_r}{T_a} = 1$ , the minimum and maximum change which maintenance can produce in productivity would be -50% and 50% respectively. However for the case when  $\frac{T_d + T_r}{T_a} \gg 1$ , maintenance would produce a maximum change of 100% in the value of productivity, which shows usefulness of maintenance. This indicates that unless the value of  $\frac{T_d + T_r}{T_a} \geq 1$ , maintenance should not be planned.

$$P_+^* \text{ min} = \frac{-T_a}{T_a + T_d + T_r} = \frac{-1}{1 + \frac{T_d + T_r}{T_a}} \quad \text{and} \quad P_+^* \text{ max} = \frac{T_d + T_r}{T_a + T_d + T_r} = \frac{\frac{T_d + T_r}{T_a}}{1 + \frac{T_d + T_r}{T_a}} \quad \text{Equation 12}$$

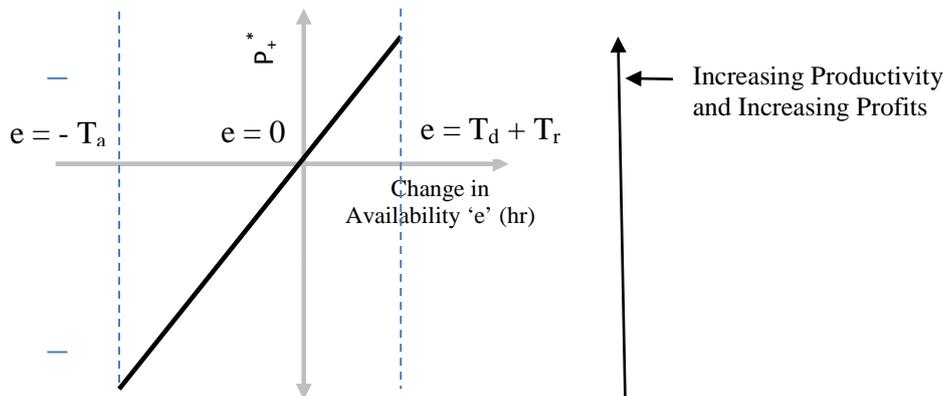


Figure 3 Schematic shows variation in productivity change with changing availability

In order to establish the conditions under which the positive effect of maintenance is maximised, let the maximum value of downtime, repair time and availability of OWT in a year be  $T_d = 1440$  hr,  $T_r = 120$  hr and  $T_a = 5256$  hr. In order to find the favourable combinations of  $T_d$ ,  $T_r$  and  $T_a$  when maintenance should be planned, let these values be divided into four equal intervals and the mid value of these intervals are taken to calculate  $((T_d + T_r)/T_a)$ . These generate 64 different values of  $((T_d + T_r)/T_a)$  however amongst them only 9 combinations of  $(T_d, T_r, T_a)$  generate a value of  $\geq 1$  for  $((T_d + T_r)/T_a)$ . These are shown as cross marks in Figure 4.

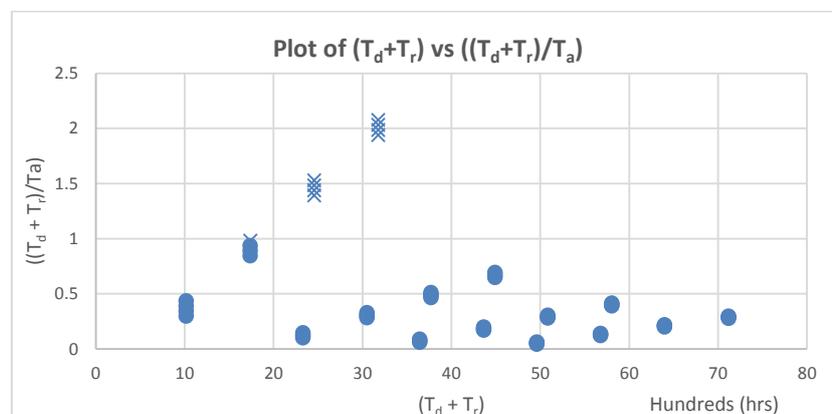


Figure 4 Shows favourable conditions when maintenance should be planned (represented by cross marks)

These cross marks represent values of  $(T_d, T_r, T_a)$  when they are (900, 15, 657), (1260, 15, 657), (900, 45, 657), (1260, 45, 657), (900, 75, 657), (1260, 75, 657), (540, 105, 657), (900, 105, 657) and (1260, 105, 657). From Figure 4 it is inferred that maintenance should be performed (i) before the value of  $(T_d + T_r)$  becomes very high, and (ii) when a failure has the potential to decrease availability of OWT to a very low value. In order to estimate financial gains achieved due to maintenance, Equation 13 can be used. So if a maintenance was to introduce positive effect on availability and productivity at 'e =  $(T_a + T_d + T_r)/2$ ', this would result in a profit as given in Equation 13(a).

$$Profit (\text{£}) = 24 C_p T_R N \left(1 + \frac{P_p}{100}\right) [e] \quad \text{Equation 13}$$

$$Profit (\text{£}) = 24 C_p T_R N \left(1 + \frac{P_p}{100}\right) \left[\frac{T_a + T_d + T_r}{2}\right] \quad \text{Equation 13a}$$

## 2.4. Reliability, Safety and Upgrade Technology

Other factors which effect maintenance decisions include reliability, safety and upgrade technology, and these are considered briefly here. Reliability is defined as a "system's ability to function under given conditions at specified time". So if failure probability density function for OWT is given by 'f (z)', Reliability  $R(t)$  is found from:

$$R(t) = P_r(t_1 < z < t) = 1 - \int_{t_1}^t f(z) dz$$

The function 'f (z)' would exhibit a higher (/lower) value at times when OWT components would exhibit more (/less) failures during a particular time interval in its failure history. So, if components have fewer failures during their lifetime, their reliability values would be higher. However a low reliability value does not imply that OWT would generate less power, rather it only provides an indication to the probability of component's failure. Whereas for an electrical system, a simple failure can make the system non-functional and require urgent servicing, in mechanical parts and civil structures, many faults can be ignored for urgent attention. So although it is important that high reliability components are used in OWT, this is especially important for critical components in an OWT. In order to maintain or improve reliability value for OWT, it is essential that (i) a proactive maintenance regime be designed for OWT maintenance, (ii) any observed failures are rectified as soon as reasonably possible, and (iii) only recommended and reliable components are used as spares. This is important since unattended, ignored or undetected failures can propagate and cause bigger faults thus reducing the overall reliability of OWT. As abrupt weather conditions cause unbalanced forces and stress, and result in premature failure, it is important that compensatory provisions are designed to counter the impact of fluctuating weather without reducing the reliability of OWT and its components.

Ensuring safety of workers and assets is a legal and moral responsibility of both workers and businesses and can have financial implications and add to operational costs. For example in a case involving accident, that introduces ' $T_{\text{Accident}}$ ' (hr) downtime/year, raises insurance premium (£P) by 'p%', and incurs compensation (£B) and administration charges (£C) for that year, the total revenue lost would be:

$$C_{\text{Safety}}(\text{£}) = 24 C_p T_R N \left(1 + \frac{P_p}{100}\right) T_{\text{Accident}} + \frac{P}{100} * P + B + C \quad \text{Equation 14}$$

In order to avoid increasing operational costs, safety needs should be met.

With advancements made in OWT technology, new and more reliable parts are now being manufactured to improve reliability, availability, productivity and safety in OWT. Any technology that reduces downtime ( $T_d$ ), faults ( $k_i$ ) and reduces repair time ( $T_r$ ) would invariably reduce the overall lifetime cost of maintenance. However such an upgrade should also offer cost benefits during the lifetime of OWT, i.e. cost of upgrading should increase profits that can be generated from OWT by incorporating such technology. If downtime of an OWT is reduced by 'h' (hr) due to upgrade technology, the corresponding values of change in Productivity and profitability would be as shown in Equation 15 and Equation 16 respectively. This is accordance to Equation 7 and Equation 8.

$$P_{+ \text{ Upgrade}}^* = \left\{ \frac{h}{T_a + T_d + T_r} \right\} \quad \text{Equation 15}$$

$$Profit_{\text{Upgrade}}(\text{£}) = 24 C_p T_R N \left(1 + \frac{P_p}{100}\right) h \quad \text{Equation 16}$$

In continuation with the example discussed in Section 2.2, suppose for example that an upgrade technology reduced downtime by '20 hr' (= h) (i.e. from 720 hr to 700 hr) and improved performance by '5%' (=φ) in the productive time of an offshore wind farm containing 50 in number 2MW OWT that was instead generating 1.8MW, this would increase the availability of the 10 defective OWT from 91.52% to 91.76%, and assist in the generation of £7.65M of additional revenue each year from the wind farm or ~£85,000/MW. If this technology was to be introduced after the warranty period (usually 5 years) and it was to operate for the remaining lifetime (15 yr), the wind farm would generate an additional income of £114.75M. Considering a profit margin of 50%, an upgrade technology whose cost  $x \leq \sim \text{£}50\text{M}$  would be considered to be a good investment.

Electrical Systems reportedly contribute towards 25%<sup>6</sup>- 45%<sup>7</sup> of all failures in wind turbines. In many instances these failures are inexpensive to repair and maintain, however due to associate offshore costs it becomes costly to rectify these frequently occurring failures. Consider a scenario where issue lies with the software of the control system that regulates the pitch and yaw systems for OWT. If this control system is known to be inefficient and at times required OWT to be switched off for 2 working days (48 hours = h) for repairing and testing each OWT. If the software of these control systems were to be updated for a wind farm containing 50 (=N)

2MW (=T<sub>R</sub>) OWT, taking 5256 hr to be the total number of productive period for an OWT and profit percentage (P<sub>P</sub>) as 25%, the improvements made in this wind farm due to software update would be:

$$A_{Upgrade} = \frac{h}{T_a + T_d + T_r} = \frac{48}{5256} * 100 = 0.91\% ; \quad P_{+ Upgrade}^* \sim \frac{h}{T_a + T_d + T_r} = 0.91\%$$

$$Profit_{Upgrade} (\text{£}) = 24 C_P T_R N \left(1 + \frac{P_P}{100}\right) h = \text{£}19.44M/year$$

$$Profit \text{ for 15 years} = \text{£}291.6M$$

So an acceptable cost of upgrade technology (< 0.5 \* Profit for 15 years) would be £145M.

### 3. Conclusion

High availability, reliability, safety and productivity, and use of cost effective upgrade technology can enhance the working and profitability of OWT. This work looked at these criterions as an extension of previous work published regarding OWT maintenance. This work demonstrates that with greater insight into the above five areas, better and more productive maintenance can be planned for OWT. The equations offer ways to calculate whether changing maintenance practices will benefit financially and whether new upgrade technology will result in significant functional benefits over the lifetime of the OWT farm. It is concluded from this work that the OWT maintenance decision model suggested in Figure 1 provides good guidance into making maintenance decisions without compromising on profits.

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