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EFFECT OF PREVENTIVE MAINTENANCE INTERVALS ON RELIABILITY AND MAINTENANCE COSTS OF WIND TURBINE GEARBOXES

Abstract

As many of the installed wind turbines (WTs) get older or approach their design life, there will be a drive to keep extending the lives of the main components especially the gearbox. The challenge of operations and maintenance (O&M) will potentially be even more as there will be a need to keep the cost to a minimum. Similarly, as years of experience of operating WTs accumulates, knowledge about the behaviour and failure of subsystems is gained as well. Also with good documentation and repository of historical operational, performance and failure data, future decisions of O&M can be taken based on insights from past experience. This paper presents an approach for implementing preventive maintenance (PM) by using historical failure data to determine the optimal PM interval required to maintain desired reliability of a typical module or subassembly. This paper builds upon previous research in the area of WT gearbox reliability analysis and prediction, taking it further by examining the relationships between the frequency of a PM task and the reliability, availability and maintenance costs. The approach presented demonstrates how historical in-service failure data can be used in PM task selection based on the minimum maintenance cost and maximum availability. Available historical field failure data of the High Speed Module of a Vestas 2MW WT gearbox is used to validate the approach and show its practicality. The results of this study are then presented – indicating that choosing the right PM interval based on the minimum unit maintenance cost and maximum availability also improves WT gearbox reliability.

1 Introduction

WTs have come a long way as a proven source of energy, currently generating over 3% of the global energy consumption [1]. As the demand for low carbon – environmentally friendly – forms of energy increases, WTs would keep playing a major role to meeting this demand. However, it is well known from literature that WTs, in the past two decades, have had issues with high failure rates of subassemblies [2]–[5]. Although the performance and efficiency of turbines have improved considerably [5], a lot still needs to be done to reduce the long term costs of operating the turbines. Contributing to these long term costs are the failure rates, associated downtimes and repair costs of WT subassemblies. Reducing these three factors is a key driver towards having a more proactive maintenance strategy during the service life of a WT. Other factors such as logistics/supply chain planning and the prediction spares consumption – which also contribute to long term O&M costs – are either directly or indirectly related to the failure rates, downtime and cost of repair. Hence being able to prevent failures or avoid the consequences, reduce downtime and repair costs should help wind farm (WF) operators lower their O&M costs over the service life of the turbines.

As many of the installed WT near their design life, there will be a drive to keep extending the lives of the main components especially the gearbox. The challenge of O&M will potentially be even more as there will be a need to keep the O&M cost to a minimum. Furthermore, with the previous experiences of running similar WTs over decades, the failure behaviour of each main component and module would have been understood to a great extent. Hence, the use of historical data can come in handy

when choosing the right maintenance strategy which would arise to the minimum O&M cost. But it is well known that O&M costs are of the order of up to 20% or more of the total life cycle costs [6], and need to keep it lower than 20% could make the selection of the right maintenance strategy a challenge. For WTs, this could be considerable greater due to the portion of unscheduled maintenance costs which Walford [6] suggests are hard to predict at the start of a project. Hence a shift towards more preventive and condition based maintenance strategy is needed so as to reduce the O&M costs, thus improving the profitability of wind projects.

This paper presents an approach of selecting a suitable PM strategy with the aim of minimising the cost of O&M, through the use of historical in-service data. The specific contribution this paper presents, is a methodology for combining the unit maintenance cost, desired reliability and maximum availability of a gearbox module, as optimisation criteria for selecting a suitable PM interval, when field failure data is available. WF operators and O&M managers can find this methodology particularly valuable not only because they can apply it in selecting the right maintenance strategy, but because they can also assess the economic and technical feasibility of PM compared to other maintenance strategies. Before going into the details of the proposed approach, the next section will explore previous literature in the area of reliability, availability, maintainability and safety (RAMS) relevant to WT gearbox.

2 RAMS OF WIND TURBINE GEARBOXES

2.1 RELIABILITY PREDICTION

In the last two decades there has been an increased focus on analysing and predicting the reliability of WTs and their subassemblies, especially the gearbox. This is as a result of wanting to understand and eliminate the causes of higher than anticipated failure rates of WT subassemblies. Of notable contribution are the works done by the EU Reliawind consortium [7], Supergen wind energy technologies consortium in the UK [8], DOWEC wind project in the Netherlands [9] and also NREL [10] in the United States of America – to name a few. In particular, with respect to avoiding failures, a lot has been done by both the research community and the wind industry to eliminate early failures through several design improvements. A noticeable example was the change of the bearing selection of the high speed and intermediate speed modules from spherical roller bearings to tapered roller bearings [4]. This type of design change can reduce the risk of failure considerably. When design changes cannot be made easily, other alternatives such as the selection of the right maintenance strategy can be adopted to prevent failures or at least, reduce their consequences. Furthermore, from a gearbox reliability prediction perspective, Smolders *et. al.* [11] presented an approach for predicting an analysing the reliability of WT gearboxes. This approach broke down the gearbox into modules which are connected in series on a reliability block diagram (RBD). Figure 1 below shows a series RBD connection of the main modules of a typical Vestas V90 2MW gearbox. The authors have chosen this gearbox to be used in this paper for two reasons:

1. The availability of some in-service data of a sample population of this class of turbines, which will help validate the approach of using historical data for maintenance planning.
2. The arrangement of the gearbox modules are very similar to the R80 configuration presented by Smolders *et. al.* [11], which makes it possible to build upon previous literature.
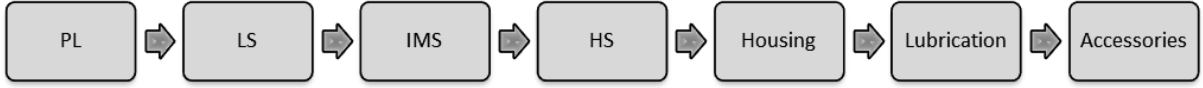
FIGURE 1: RELIABILITY BLOCK DIAGRAM OF GEARBOX ASSEMBLY

The acronyms PL, LS, IMS, and HS stand for the planetary, low speed, intermediate speed and high speed modules respectively. Also Lubrication and accessories can be shortened to "LUB" and "ACC" respectively. From a reliability perspective, for a system made up of elements connected in series, each individual element has to function before the entire system can be functional. Consequently since reliability is a probability[1], the reliability of a series system is then equal to the product of the individual reliabilities of each element. Hence for the RBD shown in figure 1, the reliability of the gearbox is given as:

$$R(t)_{gbx} = R(t)_{pl} \times R(t)_{ls} \times R(t)_{ims} \times R(t)_{hs} \times R(t)_{housing} \times R(t)_{lub} \times R(t)_{acc} \qquad (1)$$

There are several methods for estimating the individual module reliabilities. The recommended way of estimating each module's reliability would be to make use of the historical field failure data which can be modelled parametrically by theoretical probability distributions such as Weibull. For instance, the reliability estimate for a two parameter Weibull distribution is given as:

$$R(t) = e^{-\left(\frac{t}{\eta}\right)^{\beta}} \qquad (2)$$

Where, β and η are the shape and scale parameters of the Weibull distribution respectively. If historical values of β and η are known, they are immediately used to calculate the reliabilities but otherwise, the historical times to failure of each module would have to be plotted on a Weibull paper to determine their respective values for β and η. As the latter is beyond the scope of this paper, the authors will make use of the historical values of β and η to estimate the reliabilities where such data exist. When historical parameters and times to failure are unavailable, another alternative is to estimate the failure rates. For example, Smolders *et. al.* [11] used reliability estimates from Naval standards [12] to estimate the failure rates of each module due to the unavailability of historical data. With such estimates, the relationship between the failure rates and reliability of each module then becomes:

$$R(t) = e^{-\lambda t} \qquad (3)$$

Where λ is the failure rate usually expressed in number or failures per unit time *t*. Based on the findings by Smolders *et. al.* [11], the most un-reliable module of the three stage gearbox is HS parallel stage, due to its high speed operation [13]. Furthermore most gearbox failures appear to initiate at bearing locations which many later spread to the gear teeth as bearing debris [3]. This is also true for the HS bearing whose failure may lead to consequential damage of the intermediate module, via debris, if not discovered early enough. Many authors have presented different techniques for monitoring the gearbox and especially the HS bearing. These ranges from monitoring and analysing of SCADA signals [13]–[21] to vibration analysis [22]–[28], and other condition monitoring techniques [29]–[31], used for predicting and diagnosing incipient gearbox failures. The authors agree with these techniques, but argue that there has been little done in previous literature to

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[1] Reliability is the probability that a system (or component) performs a function under stated conditions for a stated period of time.

understand how PM tasks can be exploited to either prevent or manage the consequences of the failure of gearbox modules upon the availability of historical data. A good justification for this is that for turbines such as the V90, it is possible to perform repair tasks on the HS and IMS module inside the turbine without the need of any external crane. This avoids the cost of mobilising heavy cranes and equipment (vessels in offshore applications) needed to exchange or service a complete gearbox or modules such as the planetary stage.

2.2 MAINTENANCE TASKS

Before going any further, it is necessary to distinguish between a maintenance task and a maintenance strategy. A maintenance strategy is a long term plan covering all the aspects of maintenance management and sets the direction of maintenance management[2]. However, a maintenance task is any set of activities which are required to be performed, in a specified manner, by the user in order to maintain a system's functional state [32]. Knezevic, in his book [32], classified the maintenance tasks into the three generic classes: corrective, preventive and conditional maintenance tasks. Moubray [33] classified maintenance tasks into two groups: (1) proactive tasks – which are preventive and predictive maintenance tasks and (2) default actions – which are the corrective measures put in place once proactive tasks are not technically feasible. It can be suggested that majority of literature in the field of RAMS would agree with the classifications above. PM has the primary aim of avoiding failure or at least reducing the failure consequences [33]. "… a proactive task is only *worth doing* if it deals successfully with the consequences of the failure mode(s) which it is meant to prevent" [34]. Furthermore, Moubray [33] suggests that From a technical view point, there are two key issues that dominate a proactive task selection:

- The relationship between the age of the item under consideration and its likelihood of failure
- What happens once a failure has started to occur (failure consequences)

The authors agree with Moubray [33] but also argue that the economic feasibility should be considered as well when selecting a proactive – PM – task, in line with Knezevic's [32] approach towards maintenance optimisation. Hence, this paper will examine both the technical and economic feasibility for PM scheduling.

From a WT gearbox perspective, maintenance tasks can be further classified by the nature of the task. Maintenance tasks, be it inspection, repair or replacement, can be either performed inside the nacelle of the turbine – called "Up-tower tasks" or can be performed outside the turbine – called "Down-tower tasks". For example, the replacement of an oil filter, changing of the oil and visual inspections would fall into an up-tower category. However, a major overhaul or replacement of a main component such as replacing the gearbox, or some of its modules, can only be done outside the turbine and would require external crane and tooling. This makes a lot of difference in the O&M costs especially for offshore turbines where a vessel and/or helicopter would be needed alongside a crane to make replacements. In current WT designs such as the Vestas V90 2MW, there exists an internal crane inside the nacelle, which enables further up-tower tasks to be done. Two notable examples are the ability to replace or repair the HS and IMS modules up-tower for some gearbox designs. This additional design feature has paved way for improving the times to repair and lowering the O&M costs by doing away with the painful logistics that accompany a gearbox exchange and as a result paying less when servicing or replacing such modules. The nature of a task, up or down-tower also determines the mean time to repair (MTTR) of the module and in general down-tower tasks have a greater MTTR.

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[2] http://www.plant-maintenance.com/terminology.shtml

3 ANALYSIS

The sole aim of this paper is to show how historical in-service failure data can be used to select the optimal PM interval. Furthermore, the use of in-service failure data validates the methodology presented in this section As mentioned in previous sections, the HS module is considered to be the least reliable module of the gearbox [11]. Fischer *et. al.* [35] – in their case study on the V90 gearbox – also agree with this identifying the HS and IMS bearing failures as the dominant failures of the V90 gearbox. The HS bearing in particular is very sensitive to lubrication, temperature and moisture, which beyond their acceptable limits will lead to excessive wear, fatigue or corrosion of the bearing [35]. Hence, the authors have selected the HS module of the V90 gearbox as a candidate for the PM task analysis.

3.1 FREQUENCY OF CORRECTIVE MAINTENANCE TASKS

A corrective maintenance (CM) task is performed after failure has occurred [32]. Consequently, the frequency of a CM task solely depends on the time to failure of the item in question. The times to failure of items in the field can be described by probability distributions, which have certain parameters. Once these parameters are known the mean time to failure (MTTF) can be determined. It follows that the frequency of a CM task is:

$$FMT^c = MTTF \tag{4}$$

This applies mainly to non-repairable systems.

3.2 FREQUENCY OF PREVENTIVE MAINTENANCE TASKS

As described earlier, PM tasks are performed at fixed intervals. These intervals are typically a function of the life distribution of the item considered [32]. According to Knezevic [32], PM interval (FMT^p) can be determined based on three optimisation criteria: minimum maintenance cost, required reliability and maximum availability.

3.2.1 BASED ON MINIMUM MAINTENANCE COST

The total direct cost of a maintenance task is on the one hand related to the cost of maintenance resources used directly during the execution of the task. On the other hand it is related to the cost of consequences, i.e. loss of revenue for the customer [32]. For CM, the latter becomes even greater for components with high downtimes especially the gearbox. Moreover, the mean cost of a PM task is still a function of the cost of CM, hence the risk of incurring costs due to revenue losses during PM. To explain further, given the optimal interval for performing PM, the projected cost of PM (CPM) would be equal to the sum of the cost of a PM task (CMT^p) and the product between the cost of a CM task (CMT^c) and the probability of failure, F(t), during that interval. This is because there is still a chance of the component failing, no matter how small, during the PM interval. Hence,

$$CPM = \begin{cases} F(FMT^p) \times CMT^c + CMT^p, & F(FMT^p) \neq 0 \\ CMT^p, & F(FMT^p) \approx 0 \end{cases} \tag{5}$$

Consequently, the average cost for a preventive task per unit of operation, for a specific interval FMT^p is given below [32]:

$$UMC^p(FMT^p) = \left[\frac{F(FMT^p) \times CMT^c + CMT^p}{FMT^p} \right]_{min} \qquad FMT^p \leq MTBF \tag{6}$$

The optimal interval (FMT^p) of the HS module can then be calculated from equation (6) by iterating to get the minimum unit PM cost. The probability of failure F(FMT^p) for the HS module can be estimated from equations (2) or (3) by substituting FMT^p as time t. It should be noted that both the PM and CM costs would vary for offshore and onshore WFs. Furthermore, equation (6) also depends on the probability of failure and on how large the difference between the cost of CM and PM is. One may notice in practice that if the PM cost is not considerably less than the CM cost, then PM tasks may not be economically feasible. A way of determining this is by projecting the PM and CM costs over the life time of the gearbox to see which is greater. This will be demonstrated in the results section.

3.2.2 PREVENTIVE MAINTENANCE AND RELIABILITY

Considering the WT gearbox and then the HS module, the relationship between the number and frequency of PM tasks on the HS module throughout the gearbox design life and the reliability will be established below.

If T_d is the design life of the gearbox and N is the total number of preventive tasks that would be performed on the HS module during the design life, the relationship between T_d and FMT^p is:

$$T_d = N \times FMT^p \tag{7}$$

Assuming each PM task restores the HS module to a condition as good as new, the system (gearbox) at a time $t > FMT^p$ will have no recollection of accumulated wear effects of the HS module at times before PM was done. Hence the reliability at the next interval $FMT^p < t < 2FMT^p$, would be a product of the probability $R(FMT^p)$ that the system has survived until the preventive task and the probability $R(t - FMT^p)$ that a system as good as new will survive for $(t - FMT^p)$ without failure. This is shown in the equation below:

$$R(t) = R(FMT^p)R(t - FMT^p), \quad for \ FMT^p \leq t < 2FMT^p \tag{8}$$

If this is repeated for N intervals in the design life equation (8) reduces to:

$$R(FMT^p) = R(FMT^p)^N R(t - N.FMT^p),$$

$$for \ N.FMT^p \ \leq t < (N + 1).FMT^p \ and \ N = 0,1,2,... \tag{9}$$

In order to analyse the effect of the PM interval of the HS module on the gearbox reliability, equation (1) can be condensed into equation (10) below where $R(t)_o$ represents the product of the reliabilities of every other module.

$$R(t)_{gbx} = R(t)_o \times R(t)_{hs} \tag{10}$$

Before applying the PM interval equation (9) to equation (10), a few assumptions are to be made to simplify the analysis:

- The authors assume that a wind turbine gearbox would be replaced at least once in the life time of a wind turbine say after 10 years. The reason behind this assumption is that antecedent literature suggest that gearboxes have historically failed to achieve their design life of 20 years [3], [36]. Furthermore, from previous reliability estimates made by Tavner *et al.* [37], in a survey of turbines in Germany and Denmark, the MTBF or gearboxes was 87,174 hours – which is roughly 10 years. Therefore, the gearbox design life used in this study would be taken as 10 years.

- Every PM task performed within the 10 year design life would restore the HS to a condition as good as new.
- The PM task can either be a HS bearing replacement, complete HS module replacement, or any other operation to restore the HS module to a good as new condition, e.g. re-lubrication and cleaning.
- Failures and repair of each module are independent; hence the reliability and maintenance of the HS module can be treated in isolation, using the HS module failure data. This is one of the most fundamental assumptions made when using RBD to model system reliability. The IEC 61078:2006 standard notes that when RBD is used, failures and repairs of individual blocks are considered to be statistically independent events [38]. However, this assumption is taken with caution, since there are some relationships between the failure modes (and mechanisms) of each module. For instance, debris from the HS bearing, can lead to consequential damage of the IMS stage gears if not detected early. Also a faulty lubrication system can lead to bearing failures. To account for such interactions, techniques such as fault tree analysis (FTA), root cause analysis (RCA), and Markov analysis can be used to model the failures of each module.
- Finally, it is assumed the individual failure rates of all other modules, when combined together, is a constant λ_o, in order to simplify the analysis further.

Based on the assumptions above and upon substitution of the PM interval, equation (10) becomes:

$$R(FMT^p)_{gbx} = R(FMT^p)^N{}_o \times R(FMT^p)^N{}_{hs} \qquad (11)$$

The second term in the R.H.S of equation (9) has not been omitted for both the HS and other modules. Their values are equal to 1 because of the assumption that the gearbox would be replaced after the design life. Furthermore, since it is assumed that all other modules have a combined constant failure rate, equation (11) can be rewritten as shown below by substituting the relevant reliability equations (2) and (3) for the R.H.S terms.

$$R(FMT^p)_{gbx} = e^{-N\lambda_o FMT^p} \times e^{-\left(N\left(\frac{FMT^p}{\eta}\right)^\beta\right)}{}_{hs} \qquad (12)$$

From equation (12) above, the reliability of the HS module is Weibull distributed while that of the other modules follow a combined exponential distribution due to the constant failure rate. The second term in the R.H.S of equation (12) can be expressed in terms of T_d [39] as:

$$e^{-\left(N^{i-\beta}\left(\frac{T_d}{\eta}\right)^\beta\right)}{}_{hs} \qquad (13)$$

3.2.3 MAXIMUM AVAILABILITY AS CRITERION FOR PM INTERVAL SELECTION

Performing PM tasks more frequently has a two sided effect. On the one hand, an increased frequency in maintenance task could reduce the downtime resulting from CM and hence improving availability [32]. However, on the other hand the more frequently PM tasks are performed the less the system is available for use [32]. In order to establish the balance between these two conflicting aspects of PM, the system availability will be expressed as a function of FMT^p. The inherent availability of a system is given as [40]:

$$A = \frac{MTTF}{MTTF + MTTR} \qquad (14)$$

To account for the effect of PM tasks on availability, the terms in equation (14) can be modified as:

$$A(FMT^p) = \left[\frac{MTTF}{MTTF + MTTR + F(FMT^p) \times MTTR}\right]_{max} \qquad (15)$$

The extra term in the denominator, i.e. the product "$F(FMT^p)\ X\ MTTR$", represents the probability of performing a maintenance task if the component fails before the PM interval. The optimal PM interval can then be determined by iterating equation (15). It is useful to note that the MTBF can be used in place of the MTTF in equation (15) when dealing with repairable systems.

4 RESULTS AND DISCUSSION

As mentioned earlier, the V90 2MW gearbox has been chosen to demonstrate the approach presented in section 3. Weibull shape parameter and MTBF of the HS module has been obtained from in-service V90 gearboxes. For the other modules of the gearbox, the Authors will use the failure rates as estimated by Smolders *et. al.* [11]. This should give a reasonably practical result since the PM optimisation is being done for the HS module and also because it has been assumed previously that all other modules have a combined constant failure rate. For the purpose of commercial sensitivity, the authors have elected to assume the values of the O&M costs within reasonable limits. This assumption does not remove the practicality from the results presented in this paper because the unit maintenance cost (UMC) per PM interval is used as a PM optimisation criterion. Moreover, it will be shown in this section that UMC is also a function of the failure probabilities, which are estimated from in-service failure data provided. This reduces the sensitivity of the analysis to actual cost values hence making it possible to use assumed values for O&M costs.

4.1 SELECTING THE RIGHT PM INTERVAL

In any service engineering application, after safety, the economics is the next factor to consider before maintenance decisions are made. WT O&M is no exception to this. To this effect, the authors have chosen the minimum unit PM cost as a criterion for optimising the PM interval. Table 1 presents the data which has been used for this analysis.

Maintainability Parameters	Reliability parameters
Cost of HS PM task - £9,500[1]	Weibull shape parameter β for HS - 3.0[2]
Cost of CM task - £150,000[1]	HS MTBF - 35,700 hours ($\approx$ 50 months)[2]
HS MTTR - 6 hours [11]	λ_o = 0.059 based on estimates by [11]

Key: 1. Assumed reasonably close to industry average, 2. In-service failure data for V90 2MW HS module
TABLE 1: MAINTAINABILITY AND RELIABILITY PARAMETERS

4.1.1 ECONOMIC FEASIBILITY OF PM

After iterating equation (6) with the parameters above, the optimum value of FMT^p which gave the lowest unit maintenance cost was 12,960 hours (18 months). Figure 2 below shows the plot of the iterated times against the unit maintenance cost.
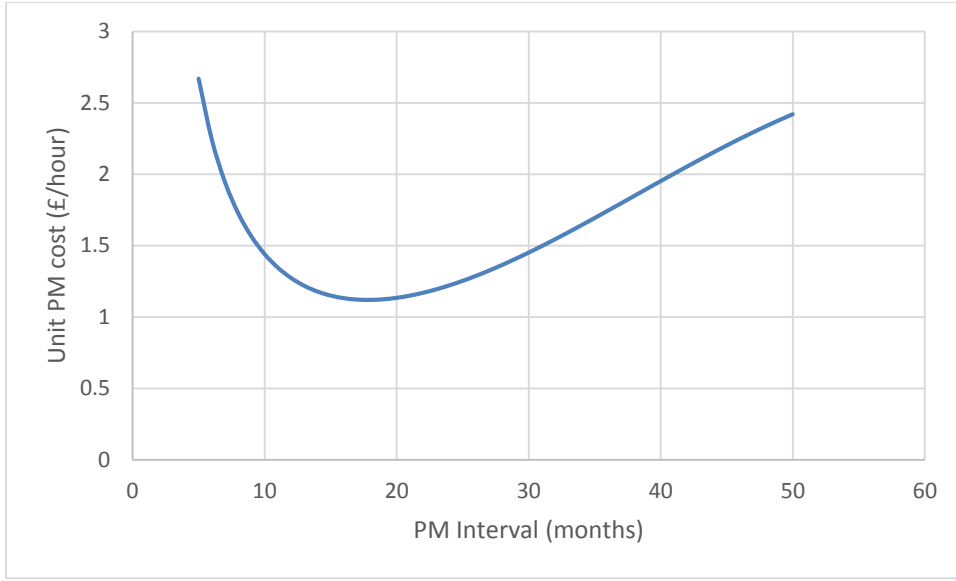
FIGURE 2: UNIT PREVENTIVE MAINTENANCE COST

In order to demonstrate the true economic feasibility of the selected PM interval, the total maintenance cost of doing PM must be compared with that if a run to failure strategy (CM) was chosen. Although in practice, the comparison should be made against the cost of selecting all other maintenance strategies and not CM only. However, due to the scope of this paper, comparison is limited to only the cost of doing CM. Referring back to the data in table 1, the mean cost of CM during the 10 year design life (CCM_d) can be calculated as shown below:

$$CCM_d = CMT^c \times \left(\frac{T_d}{MTBF}\right) = £150,000 \times \left(\frac{10 \times 365 \times 24 \ hours}{35,700 \ hours}\right) = £368,067.23$$

Where, the term (T_d/MTBF) is the number of failures within the design life. Similarly, the expected PM cost during the design life (CPM_d) can be estimated as shown below:

$$CPM_d = UMC^p \times T_d = 1.120065 \ £/hour \times (10 \times 365 \times 24 \ hours) = £98,111.72$$

From equations above, it obvious that the PM interval selected is economically feasible since the cost of CM is more than three times that if PM was done during the life time of the gearbox. It should be noted that this estimation is based on the assumed values of maintenance cost. However, since the unit maintenance costs are used in both cases ($UMC^p \ and \ UMC^c = CMT^c/MTBF$), the analysis is less sensitive to the actual maintenance costs, but rather sensitive to the ratio of both maintenance costs and the respective failure probabilities.

Hence the inequality $CPM_d << CCM_d$, governs the decision of the economic feasibility of a PM task. Substituting the appropriate terms and simplifying, the inequality can be expressed as:

$$UMC^p \ll \frac{CMT^c}{MTBF} \tag{16}$$

$$\frac{F(FMT^p) \times CMT^c + CMT^p}{FMT^p} \ll \frac{CMT^c}{MTBF} \tag{17}$$

Expressing equation (17) as the ratio of maintenance costs gives:

$$\frac{F(FMT^p) + \frac{CMT^p}{CMT^c}}{FMT^p} \ll \frac{1}{MTBF} \tag{18}$$

Hence the economic feasibility is dependent on the relationship between the probability of failure, MTBF, PM interval and the ratio of maintenance costs. If the PM interval is equal to the MTBF, the economic feasibility, equation (18) Simplyfies to:

$$\frac{CMT^p}{CMT^c} \ll 1 - F(FMT^p) \tag{19}$$

As an illustrative example the ratio of PM and CM cost can be estimated with equation (18) to test the inequality. Substituting the values for the probability of failure, PM interval length and MTBF, the inequality becomes:

$$\frac{CMT^p}{CMT^c} \ll 0.33 \tag{20}$$

Keeping CMT^c fixed at £150,000, table 2 below gives the values of the inequality in equation (20) for different values of CMT^p.

CMT^p	CMT^p / CMT^c
£ 9500.00	0.063
£ 19,000.00	0.127
£ 38,000.00	0.253
£ 76,000.00	0.507

TABLE 2: RATIO OF PM AND CM COSTS

Notice that from table 2, the PM interval becomes less economic feasible when the PM cost is doubled since the ratio 0.127 does not satisfy equation (20). This is also the case when the PM cost is increased further. Hence, there will be a threshold where the O&M manager would have to make a call on the economic feasibility once the value of CPM_d continues to approach the original cost of run to failure CCM_d. However, one should note that this analysis has been done for just PM of the HS module. Hence for true economic feasibility of the overall maintenance strategy, the costs of maintenance tasks for each module would have to be analysed as a whole and compared against a run to failure strategy for the gearbox.

This paper has chosen to use the minimum unit PM cost (economic feasibility) as an optimisation criterion for selecting the PM interval. It is also possible to select the PM interval based on the maximum availability, equation (15). However, it would be more useful to combine both optimisation criteria in selecting the PM interval. The chart in figure 3 shows the plot of the unit maintenance cost, and maximum availability for each maintenance interval. It can be seen that the maximum availability increase exponentially until reaching a steady state value at a point which closely coincides with the PM interval having the minimum maintenance cost.
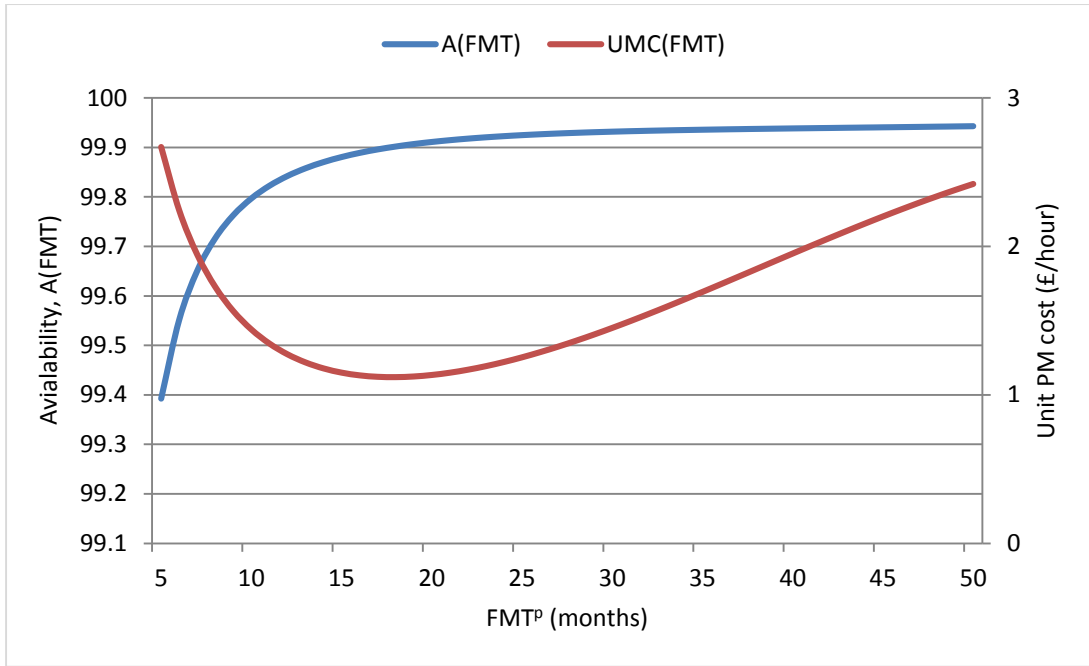
FIGURE 3: MAINTENANCE COSTS AND AVAILABILITY PER PM INTERVAL

4.1.2 *TECHNICAL FEASIBILITY OF PM*

Selecting a PM task also has to be technically feasible. Just as Moubray [33] suggested, selecting a proactive task is largely dependent on the life distribution of the item – typically, age related failures are more suited for PM. To explain this, the cost optimisation approach of equation (6) was re-iterated for values of $\beta = 0.5$ and $\beta = 1$, which indicate a burning-in and constant failure rate failure distribution respectively. The results were plotted together with the original data for $\beta = 3$ and are shown in figure 4 below:
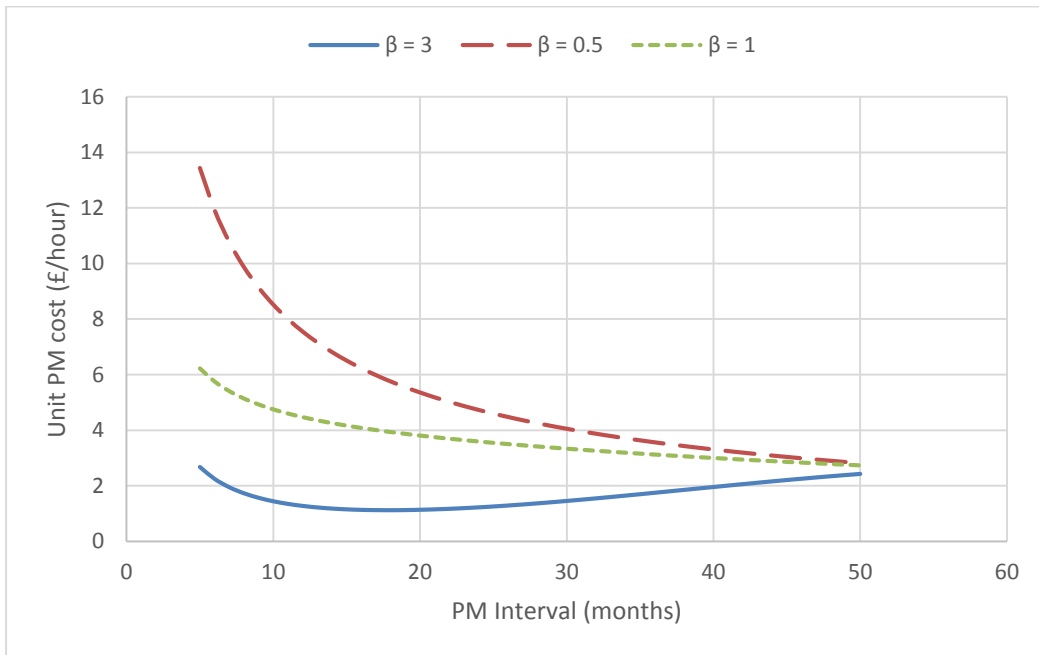

FIGURE 4: UNIT PM COSTS FOR DIFFERENT FAILURE RATE PROFILES

From figure 4, it can be seen that both β = 0.5 and β = 1, the minimum unit PM cost only occurs at the MTBF, implying that no optimal PM interval before the MTBF exists. Hence PM would not be economically and technically feasible, therefore a suitable maintenance strategy other than PM has to be adopted – either run-to-failure or condition based maintenance. In general, PM is more suitable for failures in with the failure rate increases with time. It is advised that before any maintenance strategy is considered, the technical feasibility should first be examined as this is easy to quantify with availability of in-service data. This forms the heart of the reliability centred maintenance (RCM) approach, which Moubray [33] excellently described in the seminal book "Reliability Centred Maintenance II".

4.2   IMPROVING RELIABILITY THROUGH PM

Once the optimal PM interval has been selected, it is good to understand how the PM tasks would affect reliability during the design life of the gearbox. This will in turn help the O&M manager to be able to assess the risks in performing PM prior to its implementation. Also it is necessary to identify risks because there is still a risk of failure – no matter how small – for modules with maintenance strategies other than PM and also because PM can be imperfect, hence inducing failure in the gearbox. In the case of the V90 gearbox, the gearbox reliability with and without PM was estimated making use of equations (1) and (12) respectively. Furthermore the gearbox reliability was again estimated taking into account the risk of failure being induced during PM of the HS module. The assumed probability of PM inducing a failure was chosen as 0.05. The results of these are shown in figure 5 below:
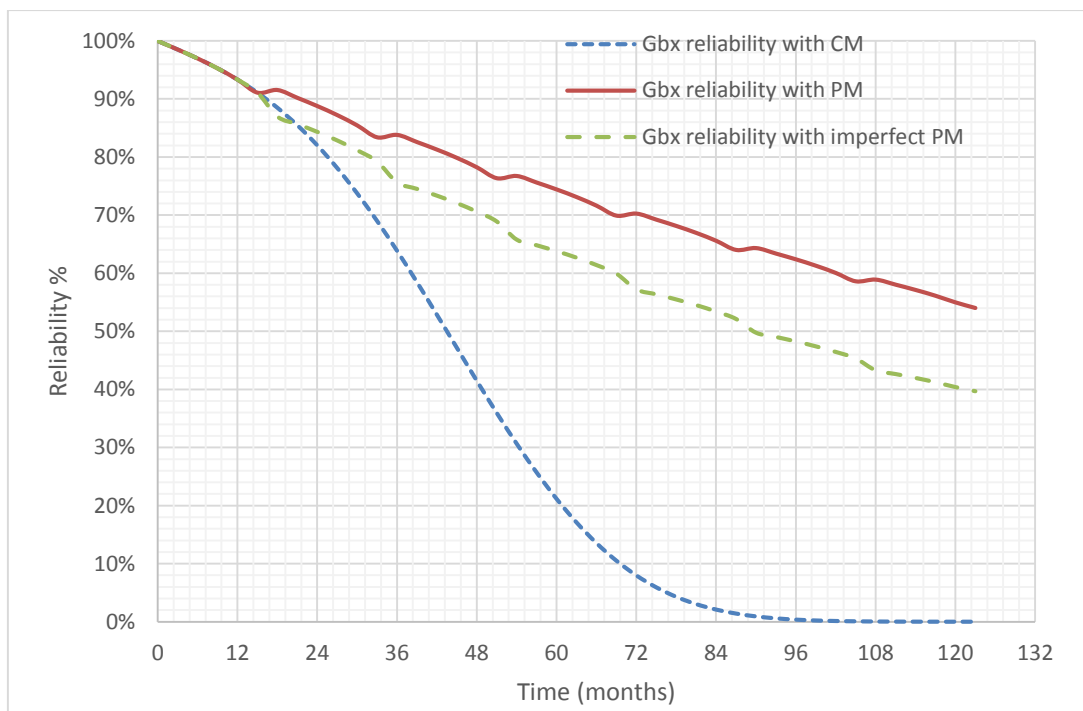

FIGURE 5: GEARBOX RELIABILITIS FOR DIFFERENT MAINTENANCE STRATEGIES

From figure 5 above, the obvious things to note are that the gearbox reliability decreases with time for each case. If a run to failure (CM) approach is chosen, the reliability decreases rapidly between the first and seventh year of the gearbox lifetime, approaching zero after eight years (96 months). When PM is done, the reliability profile reduces at a steady pace through the life of the gearbox but never reaches zero – which is the sole aim of maintenance. The difference between the reliability profiles

for PM and imperfect PM is that the rate of decrease in reliability is more for imperfect PM. Also, the probabilities of failure at each interval are greater for imperfect PM than that of PM. With CM, the reliability at half the gearbox life (5 years/60 months) is only 20% which implies that the probability the gearbox would fail at the fifth year of operation is 80% if no maintenance is done.

4.3   IMPLEMENTING PM WITH OTHER MAINTENANCE STRATEGIES

It is well known from literature that continuous monitoring through CMS and SCADA are very useful ways of sensing and identifying abnormal operating conditions, which give insight to the state of gearboxes. However, there are challenges in conveying and interpreting datasets and results from such analyses in a convincing manner to WT specialists [13]. Hence complementing CMS and SCADA reports with other dimensions of WT gearbox health information can prove valuable in getting the buy-in of specialists and in turn, making key maintenance decisions on time. This can be accomplished is by integrating predictions and results of CMS and SCADA analysis to PM tasks and vice versa. Two ways of achieving this include:

1. Making use of historical and real-time CMS and SCADA trends of key parameters such as vibration, temperature, moisture and particle counts, to inform PM tasks whenever PM intervals approach. This can aid decision making on whether to replace, repair or just inspect the item under consideration for PM.
2. Using the reports from visual inspections during PM to complement CMS and SCADA analysis.

The first point can be useful when there is still some uncertainty of the actual failure distribution of the item selected for PM. Knowing how the deterioration of the item progresses in-between PM intervals, can aid further refinement of the PM process by either extending the interval further or in choosing between a preventive inspection rather than a replacement. Once the optimal PM interval is approaching, engineers can request for CMS and SCADA analysis of the vibration, temperature, moisture and other monitored parameters. These, alongside real-time data, can be compared with previous values taken before and after the preceding PM interval so as to know the state of the monitored unit and whether or not to perform a PM inspection or replacement of the unit. For the second point, scheduled visual inspections of other modules such as the PL and LS, which are not candidates for PM can be introduced into the PM schedule. This visual inspection technique is now increasingly applied to the V90 2MW and majority of contemporary WTs by the means of a borescope inspection (also known as endoscopy) [35]. The digital photography produced by such inspections give clear indication of where the damage is and to what extent the deterioration has progressed – if any. This complements results from CMS and SCADA analysis and will promote better understanding of such results/data-sets once specialists can see the actual gears and bearings to assess their condition. Other forms of inspections include the use of swarf magnet to check for particles in the gearbox and taking oil samples oil analysis. These methods can be used as for correlation if done and recorded at regular intervals (say at every FMT^p), thus giving some insight to the degree of deterioration of the gearbox over time.

Another valuable aspect resulting from implementing PM in the overall maintenance strategy is in its potential application in offshore WTs. The ability to combine weather forecasts with PM task information can give O&M managers the advantage of anticipating weather and environmental conditions when planning the logistics for PM tasks. This reduces the risks that are attributed to the accessibility of offshore WFs during rough sea and weather conditions and the delays that may arise from hiring vessels for maintenance tasks (which are not needed in the case of up-tower PM tasks)

In summary, the PM approach presented can be used to shape long term maintenance strategy by:

- Providing a basis for better scheduling of preventive tasks and planning ahead to avoid downtime through logistical delays.
- Giving more insight into knowledge of possible spare part consumption, making it more regulated and predictable.
- Providing time to plan and prepare without the need for "fire-fighting" when failure occurs or rather if imminent failure is sensed by online monitoring systems with little time to react.

5 CONCLUSION

This paper has presented a methodology for selecting the optimal PM interval of a gearbox HS module based on the minimum maintenance costs, maximum availability and desired reliability. The approach was demonstrated and validated using in-service failure data of the HS module of the V90 2MW. The HS module was chosen as a candidate for PM due to the fact that it is considered to be the least reliable module of the WT gearbox according to previous literature and also because of the ability to perform up-tower repairs on it. The results from the analysis indicate that for an optimal PM interval to exist, the PM task has to be economically and technically feasible. The economic feasibility is a function of the unit maintenance costs, the MTBF and the length of the PM interval. The technical feasibility depends on the failure pattern of the HS module, where only age related failures tend to be suited for PM.

Being able to identify the PM interval based on the failure behaviour of HS module helps the O&M manager in planning well in advance, the resource and logistics requirements for PM; hence reducing downtime and saving cost. The reduction in downtime and cost is not only attributed to the preventive nature of the maintenance task, but also because of the cost and time saved in up-tower repairs of the HS module as opposed to down-tower replacement of the entire gearbox. This has even more impact in offshore applications, where down-tower replacement tasks require heavy lifting cranes and vessels, which incur huge costs. Moreover, knowing the optimal PM interval can also make O&M managers of offshore WFs plan for the PM task in anticipation of the weather conditions.

Perhaps one of the limitations of this research lies in the assumptions made in order to simplify the analysis, one of which was that the combined reliability of all other modules of the gearbox were assumed to have a constant failure rate. This is a simplification from practical applications where are rather not constant. However, the use of historical values for the HS gives a near to reality representation of the results. Furthermore, the failures of each module were assumed to be independent. This is an assumption that comes with the use of RBD as a modelling technique. In order to address these limitations, future work related to this research can implement the proposed techniques on for an entire gearbox assembly, modelling the reliabilities of each module and assessing the economic and technical feasibilities of performing PM on them. However, for such approach to be validated, access to entire gearbox failure and repair data would be needed from WF operators or WT manufacturers. Future research can also look at applying techniques such as FTA, RCA and Markov analysis to account for the interdependence of component and module failures and repairs in the PM interval selection.

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