Maintenance Strategies Integrating Environmental Impact for Wind Turbine Gear Trains

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Abstract. This paper develops optimized maintenance strategies for wind turbine gear trains by monitoring lubricating oil particulate contamination. Two strategies are proposed to minimize the total expected cost per unit time over an operational horizon. The first strategy employs periodic imperfect maintenance (oil filtration) when a contamination threshold is reached. The second, more comprehensive strategy combines filtration with periodic complete oil changes. Mathematical models are developed for both, integrating costs of maintenance, production losses, and environmental taxes for filtration and oil disposal. Using numerical data based on a real wind farm context, the models are optimized. Results demonstrate that the combined strategy (filtration and oil change) yields a significant cost reduction of 19.06% compared to the filtration-only approach, while also extending the preventive maintenance interval. This study provides a decision-making framework that balances economic and environmental considerations for gear train maintenance.

Keywords: Wind energy; Preventive maintenance; Gearbox; Optimization; Environmental impact.

INTRODUCTION

Wind energy has emerged as a key pillar of the renewable energy mix over the past twenty years. According to recent studies published in Renewable Energy Focus, this rapidly growing technology now accounts for nearly 7% of global electricity generation and is inevitably experiencing the fastest growth of all clean energies (Ren et al., 2024). Projections from the Global Energy Monitor (GWEC, 2023) indicate that global installed capacity could reach 1,500 GW by 2030, with an average annual growth of 12%. This rapid expansion is mainly explained by the continuous decline in production costs, around 40% since 2010 according to IRENA (Renewable Energy Agency, 2024), by the significant improvement in turbine efficiency and by increased political support in major economies. Among other things, research conducted by (The Sustainable Energy Imperative, 2024)has shown that new 15 MW offshore turbines, with 115-meter blades, can produce up to 80 GWh annually, which could power approximately 20,000 homes. These advances are based on lighter and stronger composite materials (Carbon Fiber Reinforced Polymers), intelligent control systems that optimize blade orientation, and more efficient generators.

To ensure the safe and efficient operation of a wind turbine, maintenance is necessary. This includes inspections and lubrication to reduce wear and friction of mechanical parts and components of the wind turbine gearbox. Lubrication is often applied to gears, bearings, and other moving parts. According to (Gonçalves & Silva, 2011), spectrographic analysis of used oils reveals that nearly 65% of premature gearbox failures are related to particulate contamination or degradation of lubricating properties. This study also corroborates the work of (Chen et al., 2024), who confirm that metal particles smaller than 10 microns, often overlooked in conventional protocols, contribute significantly to gear wear. It is therefore clear that one of the most important and critical components of a wind turbine is the speed gearbox, which ensures internal power transfer. The study conducted by (Aafif et al., 2022) provides valuable insights into the optimization of wind turbine gearbox maintenance policies in complex operational contexts. However, beyond economic and reliability considerations, wind turbine maintenance must increasingly integrate its direct environmental impact. Although they produce renewable energy, maintenance operations, particularly fluid management, generate potentially polluting waste. Lubricating oil draining and filtration produce used oils and filters contaminated with heavy metals, the improper disposal of which can contaminate soil and groundwater. Thus, for a 2 MW wind turbine, the typical gearbox capacity is approximately 200 to 400 liters of lube oil, as specified in the technical data of the Vestas and Gamesa models. According to (Wang & Wang, 2015), a 2 MW wind turbine can require up to 300 liters of lubricating oil in its gearbox, with periodic oil changes generating hazardous waste. According to (Sayed et al., 2021), environmental costs represent 8 to 12% of the total maintenance cost of European wind farms and according to the analysis of (Kaldellis & Boulogiorgou, 2024), a maintenance intervention generates on average 50 to 100 kg CO_2 eq for filtration and 150 to 300 kg CO_2 eq for a complete oil change. For this reason, environmental regulations such as the European (Directive - 2008/98 - EN - EUR-Lex, n.d.) impose strict treatment of this special waste. Thus, any maintenance optimization model must integrate the costs and impacts related to this environmental footprint of interventions.

This work is an extension of the study carried out on the gear trains of wind turbine gearboxes by monitoring the particulate contamination of the lubricating oil. The contributions of this article consist, firstly, in proposing and optimizing a new maintenance policy to reduce the effect of production loss at each filtration of the gearbox lubricating oil. This policy will involve systematically imperfect maintenance actions on a periodic basis to reduce the degradation of the gearbox gear train. Jointly, a mathematical model will be developed to determine the optimal preventive maintenance period TM1* which minimizes the expected total cost per unit of time, over a period F of operation time, considering the costs of preventive maintenance actions, filtration costs, tax cost linked to filtering, and production loss costs as well as the cost of renewing a gearbox gear train. The second contribution will not be limited to filtering but will consist in carrying out in addition to this an oil change operation, more efficient and expensive than filtering. This second maintenance strategy will have a mathematical model which will allow us to determine the TE* period to carry out the oil change but also the optimal preventive maintenance period TM2*, which minimizes the total cost expected per unit of time, over a period F of operating time, considering all the associated costs and cost of pollution and tax cost linked to emptying.

The remainder of this article is structured in such a way that the next section is devoted to the mathematical modeling and optimization of the maintenance cost of the first maintenance strategy, with filtering as a corrective operation before preventive maintenance. Then, we will model the expected cost per unit of time of the second maintenance strategy, with two operations (filtering and oil change) before preventive maintenance. A numerical example is dedicated to each strategy before moving on to a comparative section between the two strategies. Finally, the conclusions and research perspectives are presented in the last section.

IMPERFECT PREVENTIVE MAINTENANCE STRATEGY WITH ONLY FILTERING

Description

Over time, the lubricating oil in a wind turbine gear train becomes contaminated with metal particles and loses its lubricating properties. This degradation accelerates component wear and increases breakdown risk. When contamination exceeds a critical threshold, a filtration is required, causing significant production losses. To mitigate these costly shutdowns, periodic preventive maintenance is implemented. This approach reduces part wear and minimizes production losses. Finding the optimal maintenance frequency is crucial: excessively frequent maintenance is costly, while insufficient maintenance accelerates wear. The right balance optimizes costs and extends the equipment's lifespan. The objective is to determine the optimal preventive maintenance period T1* that minimizes the total expected cost per unit of time over period F. This includes costs for preventive maintenance, filtration, production losses during filtration, and gear train replacement.

Hazard Function

As in the first study, the gear train breakage function follows a Weibull distribution to which is added the impact of wind speed, which makes this function more realistic and dynamic and not fixed. This type of function is possible thanks to the Cox PH model. Function model used by (Zheng et al., 2020a)to describe the hazard function of a system operating alternately in normal and severe environments. In the study by (Gasmi et al., 2003), the risk function of the hydroelectric turbine in operation and maintenance activity was also integrated into a PH model. In turn, we will also use a PH model to describe the risk function as a function of age and wind speed.

Wind speed expression

The equation for wind speed is given by the following expression:

$$V(t) = Vo + A * Sin\ \frac{2\pi t}{Tc} \quad (1)$$

Termes of the expressions are defined as follows:

V_0 : Average wind speed (m/s)

A : Average amplitude of variations (m/s)

Tc : Period of oscillations (same units as t)

Once we have the speed expression, as in Rui Zheng's article (Zheng et al., 2020b), we will use j, the average speed representative of the wind speed for intervals of V(t), which will be used in the expression for the gear train failure rate. The goal is to give the same representative speed J for an interval of wind speed V(t). Thus, J is given by the following expression:

$$J = \frac{Vi + Vf}{2} \quad (2)$$

We note that:

Vi : Represents the first speed value of the interval

Vf : Represents the last speed value of the interval

Thus, if the wind speed (m/s) is included in the interval [0, 2] then the average speed representative of the wind speed (J) is equal to 1m/s. If the wind speed is between [3, 5] then J equal to 4m/s. And if it is between [6, 8] then J is equal to 7m/s and so on.

The regression coefficient

The regression coefficient θ in the Cox proportional hazards model (PH model) quantifies the impact of wind speed on the failure rate of wind turbines. It generally has two possibilities:

$\theta > 0$: Wind speed accelerates degradation

$\theta = 0$: Wind speed has no influence

There are several methods for estimating θ, namely:

- An estimation from failure data using a graphical method or the maximum likelihood method;
- From the literature, such as Zheng et al. or Byon & Ding with $\theta \in [0.2, 0.6]$ for gears and bearings.

The failure rate function will therefore have a form appropriate for wind turbines, composed of the basic Weibull-distributed hazard function and the exponential link function where α and β are the scale and shape parameters of a Weibull distribution, respectively, j is the representative wind speed and θ is the regression coefficient.
The failure rate is expressed as follows (the time unit being expressed in weeks):

$$\int_0^T \lambda(t)dt \quad \text{with} \quad \lambda(t)dt = \left(\frac{\beta}{\alpha}\right)\left(\frac{\beta}{\alpha}\right)^{\beta-1} * \mathrm{EXP}[\theta.J] \quad (3)$$

Analytical Model

Here, we present the mathematical framework for evaluating the total average cost of the proposed maintenance strategy. The model incorporates all operational and economic parameters related to preventive gear train management. It is essential to understand that simple oil filtering, when triggered by reaching a critical contamination threshold, does not directly improve the reliability of the gearbox gear train system. This intervention constitutes minimal maintenance. Real reliability improvement only occurs with scheduled preventive maintenance actions. Emergency filtering therefore acts as a stopgap solution, while planned maintenance offers a real improvement in long-term performance.

t	: Random variable designating the time before the particulate contamination threshold of the oil is exceeded
λ(t)	: The function of gearbox gear train failure rate. Note that the breakdown is considered as exceeding the oil contamination threshold
F	: The horizon or period of exploitation
i	: Index of successive PM periods during the operating time horizon F. i = {1, 2, 3, …}
CRG	: The cost of renewing a gear train of a gearbox
CF	: The cost of the filtering action
TF	: Tax or eco-contribution linked to filtering operations
CLP	: The cost of lost production per unit of time (€/hour)
CMP	: The unit cost of imperfect maintenance
ATC_1	: The average total cost per time unit for the first strategy
RF	: The duration of the filtering action after reaching the critical contamination threshold
ϵ	: Gearbox gear train degradation coefficient with filtering ($\epsilon > 0$)

Our study is based on the imperfect maintenance model initially developed by (Gertsbakh, 2000), which we adapted to the specific context of lubricating oil filtration in gear trains. This theoretical model describes the evolution of the failure rate after each preventive maintenance intervention, as illustrated in Fig 1.

$$\lambda_{i+1}(t) = e^{\epsilon} * \lambda_i(t) \quad (4)$$

$$\lambda_{i+1}(t) = (e^{\epsilon})^i * \lambda(t) = e^{\epsilon * i} * \lambda(t) \quad (5)$$

Note that ϵ, found empirically using linear regression (Gertsbakh, 2000), is considered a strictly positive "decay" factor. We start with a corresponding system to the one which will have started in the "new" state. $\boldsymbol{\lambda}(x)$ represents the failure rate before the first imperfect maintenance action.

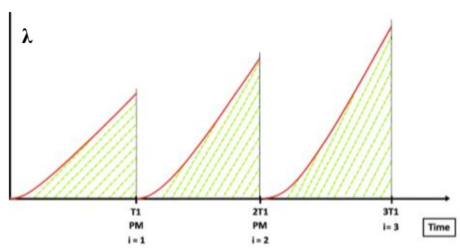

FIGURE 1. The effect of imperfect PM actions on the gearbox gear train failure rate.

Thus, the analytical expression for the expected total cost per unit time consists of the cost expressions as follows:

- The cost of the gearbox gear train, CRG.
- The cost of the filtering action and the production loss per unit of time during each PM interval. This is the cost of the CF filtering action and the tax TF, to which is added the average cost of production loss, multiplied by the average number of times the contamination threshold is reached during the PM interval.

$$\sum_{i=1}^{Int\left(\frac{F}{TM1}\right)} \left(\int_0^{TM1} e^{\epsilon * (i-1)} * \lambda(t) dt * (CF + TF + CLP * RF) \right) \quad (6)$$

- The cost of preventive maintenance which is the unit cost of an imperfect maintenance action CMP, multiplied by the number of PM intervals during the overall operating period considered F.

$$CMP * \left(Int\left(\frac{F}{TM1}\right) - (1 * M) \right) \quad (7)$$

With: $\text{Int}\left(\frac{F}{TM1}\right)$ representing the integer part of $\frac{F}{TM1}$ And $M = 1$ if $\text{Int}\left(\frac{F}{TM1}\right) = \frac{F}{TM1}$ and $M = 0$ if $\text{Int}\left(\frac{F}{TM1}\right) \neq \frac{F}{TM1}$

For more explanation, when $\text{Int}\left(\frac{F}{TM1}\right)$ is equal to $\frac{F}{TM1}$, this means that the end of the operating period H aligns precisely with the period PM. In this configuration no PM action is performed at the end of the operating period.

- The average filtering cost and production loss during the remaining operating period after the last PM action:

$$\left(\int_0^{F-\text{int}\left(\frac{F}{TM1}\right)*TM1} e^{\epsilon*\text{int}\left(\frac{F}{TM1}\right)} * \lambda(t)dt * (CF + TF + CLP * RF) \right) \tag{8}$$

This expression designates the average number of times the oil particulate contamination threshold is reached during the operating period after the last PM action, multiplied by the average filtration and production loss costs.

With all these costs defined, we can thus write our first mathematical model as follows:

$$ATC_{1(TM1)} = \frac{CRG + \left(\sum_{i=1}^{\text{Int}\left(\frac{F}{TM1}\right)} \left(\int_0^{TM1} e^{\epsilon*(i-1)} * \lambda(t)dt * (CF + TF + CLP * RF) \right) \right) + CMP * \left(\text{Int}\left(\frac{F}{TM1}\right) - (1 * M) \right) + \left(\int_0^{F-\text{int}\left(\frac{F}{TM1}\right)*TM1} e^{\epsilon*\text{int}\left(\frac{F}{TM1}\right)} * \lambda(t)dt * (CF + TF + CLP * RF) \right)}{F} \tag{9}$$

Numerical Application of First Strategy

Most of the numerical data that we used in our application and our tests of the developed model are the same used in the first study because this work is a continuation of the research carried out in the first study based on wind turbines (Genba n.d.) located in the south of Morocco. MATHEMATICA® V12.0 software was used to code the total cost per unit of time (Eq. (9)) and determine the optimal PM period TM1* with a numerical procedure. The data that we will use will be presented in table 1 below

TABLE 1. Numerical data

Notation	Numerical values
β	Weibull shape parameter $\beta = 2$
μ	Weibull Scale parameter $\mu = 200$ weeks
F	30 Years
θ	0.2
V_0	6 m/s
A	2 m/s
Tc	52 weeks
CRG	150 000 €
CF	10 000 €
TF	50 Euros
CLP	500 (€/hour)
CMP	50 000 €
RF	11 Hours
ϵ	0.005

Modeling carried out, the optimal strategy obtained in table 2 recommends that we carry out a PM preventive maintenance action every 112 weeks **(TM1*= 112 weeks)**, which roughly corresponds to a PM frequency every 26 months

TABLE 2. The obtained optimal PM interval TM1* with the corresponding minimum total cost per time unit.

TM_1*	ATC_1*
112	680.72

Imperfect Preventive Maintenance Strategy with Filtering and Emptying Operation

Description

In this second maintenance strategy, we combine filtration and oil change operations before preventive maintenance. When the oil degrades over time and the contamination threshold is reached, two levels of intervention are possible: either filtration is activated as soon as the critical contamination threshold is reached, or a complete oil change is performed after a certain number of filtrations. Oil change, which is much more costly in terms of time and resources, offers greater efficiency than filtration. The balance between these two approaches represents an essential compromise. The main objective is to determine not only the optimal time TE* for oil change, but also the ideal periodicity of preventive maintenance TM2*, in order to minimize all costs, including interventions, production losses, and possible component replacement, while maximizing equipment life.

Analytical Model

Below we present the analytical model of the average cost rate corresponding to the strategy.

t	: Random variable designating the time before the particulate contamination threshold of the oil is exceeded
λ(t)	: The function of gearbox gear train failure rate. Note that the breakdown is considered as exceeding the oil contamination threshold
F	: The horizon or period of exploitation
i	: Index of successive PM periods during the operating time horizon F. i = {1, 2, 3, …}
CF	: The cost of the filtering action
TF	: Tax or eco-contribution linked to filtering operations
TV	: Tax or eco-contribution linked to emptying operations
CP	: Cost of pollution related to emptying (€/liter)
V	: Volume of liter of lubricating oil (liter)
CRG	: The cost of renewing a gear train of a gearbox
CE	: The cost of the emptying operation
CLP	: The cost of lost production per unit of time (€/hour)
CMP	: The unit cost of imperfect maintenance
ATC_1	: The average total cost per time unit for the first strategy
RF	: The duration of the filtering action after reaching the critical contamination threshold
RE	: The duration of the emptying operation after a certain number of filtrations carried out
ϵ	: Gearbox gear train degradation coefficient with filtering ($\epsilon > 0$)
ɣ	: Gearbox gear train degradation coefficient with emptying operations (ɣ > 0)

In this second strategy, what differs from the first is above all the cost linked to filtering which changes to a cost which concerns filtering or the emptying operation.

- The cost of the filtration or draining operation and the loss of production per unit of time during each preventive maintenance interval. This is the cost of the CF filtration or CE draining operation with the associated pollution costs and taxes, to which is added the average cost of the loss of production, multiplied by the average number of times the contamination threshold is reached during the preventive maintenance interval.

$$\sum_{i=1}^{Int\left(\frac{F}{TM2}\right)} Y*\left(\int_0^{TM2} e^{\epsilon*(i-1)} * \lambda(t)dt*(CF+TF+CLP*RF)\right)+(1-Y) *\left(\int_0^{TM2} e^{\gamma*(i-1)} * \lambda(t)dt*(CE+TV+CP*V+CLP*RE)\right) \tag{10}$$

With: Y = 1 if we carry out a filtration and Y = 0 if it is an emptying operation

- The average filtering or emptying cost and production loss during the remaining operating period after the last PM action:

$$Y*\left(\int_0^{F-int\left(\frac{F}{TM2}\right)*TM2} e^{\epsilon*int\left(\frac{F}{TM2}\right)} * \lambda(t)dt*(CF+TF+CLP*RF)\right) + (1-Y) *\left(\int_0^{F-int\left(\frac{F}{TM2}\right)*TM2} e^{\gamma*int\left(\frac{F}{TM2}\right)} * \lambda(t)dt *(CE+TV+CP*V+CLP*RE)\right) \tag{11}$$

The last cost represents the average number of times the oil particulate contamination threshold is reached during the operating period after the last PM action, multiplied by the average filtration or emptying costs and production loss. The other cost components remain unchanged from the first strategy. The updated expression of the average total maintenance cost for this strategy is as follows:

$$ATC_{2(TM2)} = \frac{CRG + \sum_{i=1}^{Int\left(\frac{F}{TM2}\right)} \left(Y*\left(\int_0^{TM2} e^{\epsilon*(i-1)} * \lambda(t)dt*(CF+TF+CLP*RF)\right) + (1-Y)*\left(\int_0^{TM2} e^{\gamma*(i-1)} * \lambda(t)dt*(CE+TV+CP*V+CLP*RE)\right)\right) + CMP*\left(Int\left(\frac{F}{TM2}\right)-(1*M)\right) + \left(Y*\left(\int_0^{F-int\left(\frac{F}{TM2}\right)*TM2} e^{\epsilon*int\left(\frac{F}{TM2}\right)} * \lambda(t)dt*(CF+TF+CLP*RF)\right) + (1-Y)*\left(\int_0^{F-int\left(\frac{F}{TM2}\right)*TM2} e^{\gamma*int\left(\frac{F}{TM2}\right)} * \lambda(t)dt*(CE+TV+CP*V+CLP*RE)\right)\right)}{F} \tag{12}$$

Numerical application for second strategy

We will remain in the same context and with the same input data as in the first strategy. The objective is to simultaneously determine the optimal preventive maintenance period TM2* and the optimal period for the oil change operation TE*, thus minimizing the total cost per unit of time over the operating time horizon F.

Table 3 presents the relevant input parameters, and Table 4 presents the optimal strategy obtained.

TABLE 3. Numerical input data

Notation	Numerical values
β	Weibull shape parameter β = 2
μ	Weibull Scale parameter μ = 200 weeks
F	30 Years
θ	0.2

V_0	6 m/s
A	2 m/s
Tc	52 weeks
CRG	150 000 €
CF	10 000 €
CE	15 000 €
CLP	500 (€/hour)
TF	50 €
TV	200 €
CP	5 € / L
V	300 L
CMP	50 000 €
RF	11 Hours
RE	15 Hours
ϵ	0.005
ɣ	0.002

TABLE 4. The obtained optimal PM interval TM2* and optimal TE* with the corresponding minimum total cost per time unit.

TM_2*	TE*	ATC_2*
144	65.45	550.983

The optimal strategy therefore recommends carrying out a PM action every 144 weeks (T2* = 144 weeks), or approximately a period of 2 years. In addition, it recommends carrying out an emptying operation every 65.45 weeks (TE* = 65.45 weeks), or approximately every 15 months.

Considering the two numerical examples presented in this article, we can compare the two strategies based on their optimal costs per unit of time illustrated by Fig 2. Our study clearly shows that the two-operation approach (filtration and draining) proves to be more cost-effective than the filtration-only strategy. Indeed, without drawing a general conclusion, the cost savings associated with adopting the second strategy amount to 19.06%. However, the situation could differ depending on the configurations used in different wind farms, with different costs and gearbox reliability.

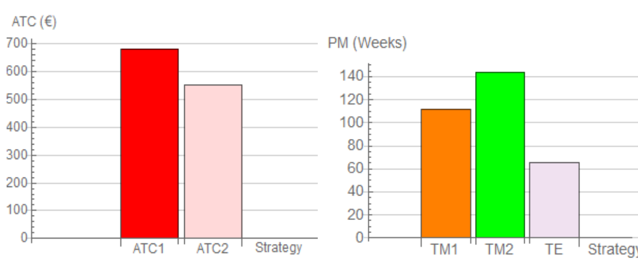

FIGURE 2. The comparison of the two strategies.

CONCLUSION

This study demonstrates that a maintenance strategy combining oil filtration with periodic oil changes is more cost-effective than using filtration alone. The quantitative results show a 19.06% reduction in total cost with the combined approach. This strategy also allows for a longer preventive maintenance interval of 144 weeks, compared to 112 weeks for the filtration-only strategy, and recommends an oil change every 65.45 weeks.

Integrating environmental costs, such as taxes and pollution fees, is crucial, as they significantly impact the overall cost-effectiveness. The findings provide a practical decision-making framework that aligns economic performance with environmental sustainability for wind turbine gearbox maintenance. Future integration of artificial intelligence could further optimize these strategies through predictive analytics.

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