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Optimal Maintenance Policy for Wind Turbine Gearbox with Minimum Requirement For Full Capacity Operation

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Abstract

This study investigates a commonly used maintenance strategy for wind turbine gearboxes in a wind farm located in southern Morocco. The gearbox condition is monitored through temperature sensors, and when a critical temperature threshold is reached, the turbine's production rate is deliberately reduced to facilitate cooling. After a predefined cooling period, the turbine resumes its normal production rate. As these overheating-cooling cycles become more frequent over time, operators must decide when to replace the gearbox. The replacement involves either installing a new identical unit or refurbishing the existing one, with the timing of this decision relying solely on the judgment of the maintenance crew.

In collaboration with this wind farm, we develop an analytical model and a solution procedure to optimize the gearbox renewal period. The model balances the costs associated with production losses during cooling phases and the financial and operational impacts of gearbox renewal. A critical constraint considered in the model is the minimum Full Capacity Operating Rate (FCOR) that must be maintained throughout the renewal cycle. The optimization model determines the ideal renewal period, T*, that minimizes the total cost per unit of time while ensuring compliance with the required FCOR.The model is extensively tested using various problem instances. An example is presented, and a sensitivity analysis is conducted to evaluate the influence of gearbox reliability and production loss costs on the optimal maintenance strategy. The results underscore the importance of model- and data-driven decision-making in optimizing maintenance operations and highlight the significant impact of reliability variations on maintenance planning.

Keywords
Wind turbine maintenance, gearbox reliability, preventive maintenance optimization, operational cost minimization, and renewable energy systems.

1. Introduction
Renewable energy is now an integral part of global and national policies (Bashir et al. 2025). Motivated by the goal to decarbonize and reduce dependence on fossil fuels, wind and solar energy have gained significant prominence. Together, they have added more energy to the world than any other source, accounting for nearly 40% of the total increase in energy consumption (Energy Institute 2024). In 2023, Europe installed 18.3 GW of additional wind capacity. This historic installation brought Europe's wind capacity to an unprecedented level. The European Union is targeting 200 GW of wind capacity by the end of 2030 (European Commission 2024).

Wind turbines (WT) are the principal method for harnessing wind energy. Wind turbines are mechanical systems that endure the challenges of continuous operation, and with time, wear necessitates appropriate operation and maintenance (O&M) solutions (Márquez & Papaelias 2020). The maintenance of wind turbines encompasses more than only guaranteeing their functionality. It emphasizes optimizing performance while reducing downtime and potential production losses to guarantee sustainability and cost-effectiveness. Reliability and efficiency are critical industry concerns as an increasing number of turbines are deployed globally. Maintenance of wind turbines is essential for optimal wind energy performance. The industry is increasingly using preventative, condition-based, and predictive methodologies (Merizalde et al.2019). Costa et al. (2021) present a comprehensive assessment of wind farm maintenance strategies. The authors highlight the significant reduction in both the levelized cost of electricity and operations and maintenance expenditures in recent years. This is the result of continuous advances in wind turbine maintenance strategies, especially in offshore projects where operation and maintenance face logistical constraints and require new techniques, especially due to restricted land use.

Several researchers have focused on reducing the O&M costs of wind turbines and optimizing their reliability. Golestani et al. (2023) developed a system dynamics model for O&M planning of offshore wind farms, highlighting weather-related delays as the primary element influencing asset management. Their model predicts turbine deterioration, repair expenditures, and downtime costs, providing a versatile solution that minimizes the need for human intervention. The capacity to foresee asset management impacts represents a substantial advancement in the strategic planning of offshore wind farm maintenance.

In a recent study, Saleh et al. (2023) developed a model designed to enhance the execution of condition-based maintenance in wind farms. Their methodology integrates sophisticated Petri net modeling with Reinforcement Learning for self-adaptive maintenance, facilitating more effective decision-making through real-time data analysis. By employing this strategy, the authors attained a turbine availability of 99.4%, demonstrating that superfluous maintenance activities can be minimized by effective planning. Such simulations demonstrate that intelligent systems can significantly influence the maintenance strategies employed by the wind energy sector.

El-Naggar et al. (2023) proposed a pragmatic maintenance plan for wind turbines, grounded in comprehensive field data, enhancing the optimization of maintenance approaches. Their technique highlights the diversity of maintenance decisions that should be customized to individual turbine components. Enhancing the reliability of these subassemblies subsequently increases total wind turbine availability and operational efficiency while reducing costs.

Digital twin models have enhanced the monitoring and maintenance of wind turbines. Liu et al. (2023) recommended utilizing this technology to predict wind power output, hence enhancing the precision of energy generation forecasts through the analysis of historical weather data and current meteorological information. Su et al. (2023) tackled the deterioration issue of wind turbine generators using a stochastic differential equation model that integrates time and condition-based maintenance techniques. The author's model illustrates the true deterioration route, enabling decision-makers to reconcile dependability and cost. It accounts for the stochastic variations anticipated in turbine components, resulting in a more refined maintenance strategy that optimizes turbine operation while minimizing superfluous interventions.

Peng et al. (2023) emphasized the significance of intelligent operations and maintenance systems in forecasting turbine malfunctions. The author's paper delineates the principal components and failure modes of wind turbines and their impact on the overall cost of wind energy generating projects. Their research emphasizes that intelligent decision support systems and problem diagnostic models are essential for reducing wind turbine life-cycle costs and extending operational longevity.In a different context, addressing WT systematic preventive maintenance, Singh et al. (2023) concentrated on formulating optimal preventive maintenance (PM) programs through Fibonacci search and genetic algorithms. The authors created an economical preventive maintenance schedule utilizing wind turbine dependability models.

Aafif et al. (2022) proposed a maintenance strategy for WT gearboxes that suggests performing imperfect PM actions to mitigate the failure rate when a temperature threshold is exceeded. A mathematical model has been developed to ascertain the optimal number of preventive maintenance activities to undertake before gearbox must be replaced, as well as the ideal timing for the maintenance team to initiate preventive maintenance or replacement operations following the surpassing of the temperature threshold. This period pertains to maintenance logistics and expenditures.

Aafif et al. (2024) examined the design, operation, and maintenance of wind turbine gearboxes. The authors proposed an initial maintenance policy using periodic imperfect maintenance activities to mitigate the degradation rate. They ascertain the best preventive maintenance interval that minimizes the overall expected cost per unit of time. A second strategy proposes adopting a novel design for the wind turbine featuring two gearboxes functioning alternately. The authors identify the ideal switching intervals and preventive maintenance periods for this integrated design and maintenance strategy. Both procedures were evaluated and contrasted utilizing actual wind farm data. The findings indicate that the alternating utilization of two gearboxes is more economically viable than employing a single gearbox. The paper provides the possibility to select the more appropriate design (one or two gearboxes) for any given situation related to the gearboxes reliability and operating and maintenance costs of the WT.

Overall, the literature on wind turbine maintenance primarily focuses on systematic, predictive or condition-based maintenance policies, considering perfect and imperfect maintenance actions. While these approaches offer valuable insights, their practical implementation often overlooks operational constraints. This study, conducted in collaboration with a wind farm in southern Morocco, addresses the question of determining the best timing to replace or overhaul the gearbox of a WT. Currently, in this company and in many other wind farms, the gearboxes are replaced based on the judgment of the maintenance department after a certain number of cycles of overheating-cooling. In fact, the condition of the gearbox is monitored through its temperature. When a certain temperature threshold is reached, the production rate is significantly reduced by slowing down the wind turbine to cool the gearbox for a certain period of time before restoring the desired production rate.

Thus, the objective of this work is to develop a mathematical model that allows to find the optimal gearbox renewal period, taking into consideration the balance between the cost and duration of production loss and gearbox cooling, and the cost and duration of replacement. This optimization must also consider a minimum required Full Capacity Operating Rate (FCOR) during a renewal cycle. This constraint explicitly accounts for lower production rates during the cooling phase, and downtime during the renewal action. Therefore, the mathematical model will determine the optimal renewal period T^* of the gearbox that minimizes the total cost per time unit while satisfying a minimum required FCOR.

The remaining sections of this paper are organized as follows. Section 2 presents the analytical model, and the solving procedure. Section 3 describes the numerical implementation and optimization results, followed by a sensitivity analysis. The conclusion of the paper summarizes this work and suggests relevant research perspectives.

2. Analytical model and solution procedure

This section presents the details of the mathematical model, and the numerical algorithm developed to derive the optimal gearbox renewal period T* for any instance of the problem.

2.1 The Mathematical Model

The total expected cost per unit of time is expressed as a function of the renewal period T, the key decision variable in this study. This cost comprises three main components: (1) the average cost and duration associated with cooling the gearbox whenever its temperature exceeds the critical threshold, (2) the average revenue losses incurred during reduced-capacity operation while cooling is underway, and (3) the average cost and duration tied to renewing the gearbox. Expenses include both the direct replacement costs and the revenue loss rate during renewal.
The notation used in this work will be as follows in table 1:

Table 1. Notation.

Notation	**Definition**
T	Renewal period (decision variable)
Dcl	Mean cooling duration (hours)
Dr	Mean renewal duration (hours)
$\lambda(u)$	Failure rate at time u (gearbox failure intensity function, where u represents the random time between consecutive overheating events)
Rlc	Mean revenue loss rate during cooling (€/hour)
Rlr	Mean revenue loss rate during gearbox renewal downtime (€/hour). Note: Rlr > Rlc. Losses during renewals (no production) exceed those during cooling (reduced production rate)
Ccl	Mean cooling cost (€)
Cren	Mean renewal cost (€)
A	Minimum required full-capacity operating rate (threshold for the availability level)
FCOR(T)	Full-capacity operating rate as function of T
CTM(T)	Average total cost per unit of time as a function of T

It is important to note that cooling the gearbox, while necessary to restore normal operation, does not improve its long-term reliability. Hence, each cooling intervention is modeled as a minimal repair, meaning it addresses the immediate overheating issue without reducing the gearbox's underlying failure rate.

Hence, the analytical expression of the total expected cost per unit of time is as follows:

$$CTM(T) = \frac{(Rlc \times Dcl + Ccl) \times \left(\int_0^T \lambda(u)du\right) + (Cren + Rlr \times Dr)}{T + Dr} \tag{1}$$

The first term of the sum expresses the product of the average cost incurred every time the cooling operation is carried out (production loss during cooling and direct cooling cost), and the average number of times the temperature threshold is reached necessitating cooling during a renewal cycle. The second term represents the average cost of the renewal operation including the cost of the new gearbox, and the production loss during the renewal downtime.

To ensure operational viability, this cost minimization is subject to an availability constraint. Availability here means production at full capacity (no reduction of the WT production rate due to maintenance actions). A minimum required Full Capacity Operating Rate (FCOR), A, must be satisfied over each renewal cycle. This requirement is mathematically modeled as a constraint expressed as follows:

$$FCOR(T) = \frac{(T + Dr) - \left(Dcl \times \int_0^T \lambda(u)du + Dr\right)}{T + Dr} \geq A \tag{2}$$

The numerator of the ratio expresses the total time the turbine operates at full capacity during a renewal cycle, calculated as the duration of the cycle minus the periods for cooling and renewing the gearbox. The denominator represents the total renewal cycle duration.

Thus, the optimal renewal period T* of the gearbox will be the solution to the following constrained minimization problem:

Minimize *CTM(T)*
Subject to
FCOR(T) $\geq A$

2.2 Numerical Procedure

The flowchart in Figure 1 outlines the step-by-step computational process for determining the optimal renewal period *T**. Beginning with the input parameters (cooling duration *Dcl*, renewal duration *Dr*...), the algorithm initializes *T* and iteratively evaluates FCOR (Eq. 2). *T*1 and *T*2 represent the boundaries determined by FCOR(*T*)=*A*, defining the feasible range [*T*1, *T*2] for the optimal solution. Within this interval, the total cost *CTM*(*T*) (Eq. 1) is minimized to determine *T**. This ensures compliance with the minimum *FCOR* requirement while balancing cooling and renewal costs.

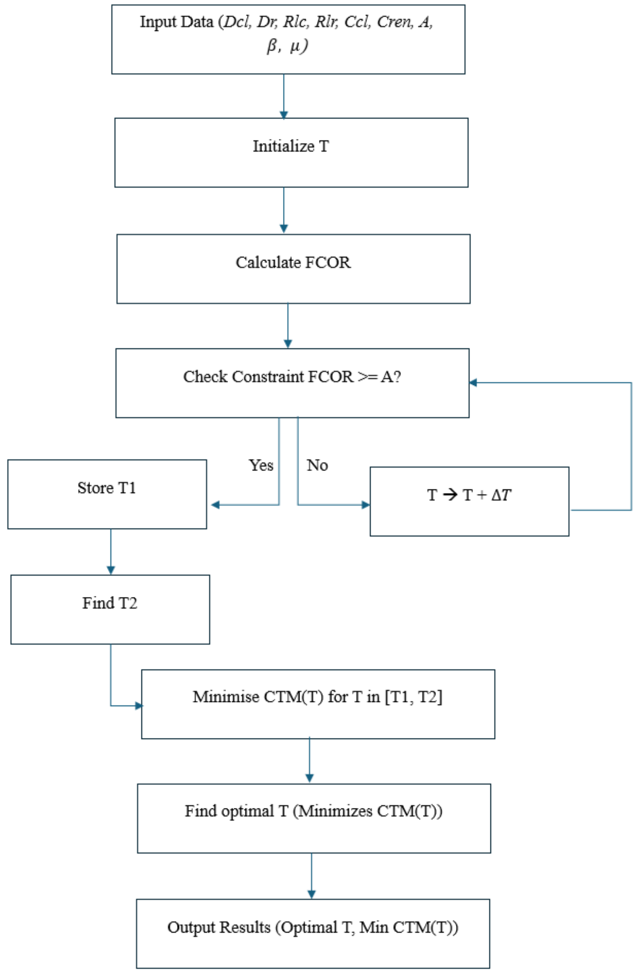

Figure 1. Numerical algorithm to find the optimal renewal strategy.

3. Numerical Results

MATHEMATICA® software (V10.2–2015) has been used to code the model and find the optimal renewal period T* for any instance of the problem with a given set of input parameters. Below is one of the numerous numerical examples used to test the model in collaboration with the wind farm in Morocco.

3.1 Illustrative Example

The time between consecutive overheating events follows a Weibull probability distribution with a shape parameter $\beta = 4$ and a scale parameter $\mu = 100$, yielding a Mean Time Between Overheating events (MTBO) of 90 weeks between successive overheating occurrences. The corresponding failure rate function is given by:

$$r(t) = \frac{\beta}{\mu} \times \left(\frac{t}{\mu}\right)^{\beta-1} \qquad \text{Eq (3)}$$

The used input data are shown in Table 2.

Table 2. Input Parameters.

Notation	**Definition**
Dcl	*25 (hours)*
Dr	*48 (hours)*
Rlc	*800 (€/hour)*
Rlr	*1 800 (€/hour)*
Ccl	*5 000 (€)*
Cren	*150 000 (€)*
A	*80%*
β	*4*
μ	*100 Weeks*

As shown in figure 2 and table 3, the average total cost per week CTM(T) reaches its minimum value (€2360/week) at the optimal renewal period T* = 134 weeks (≈2.6 years). Costs increase for shorter periods (due to frequent renewals) and longer periods (due to excessive cooling interventions), illustrating the economic rationale behind the optimized maintenance schedule.

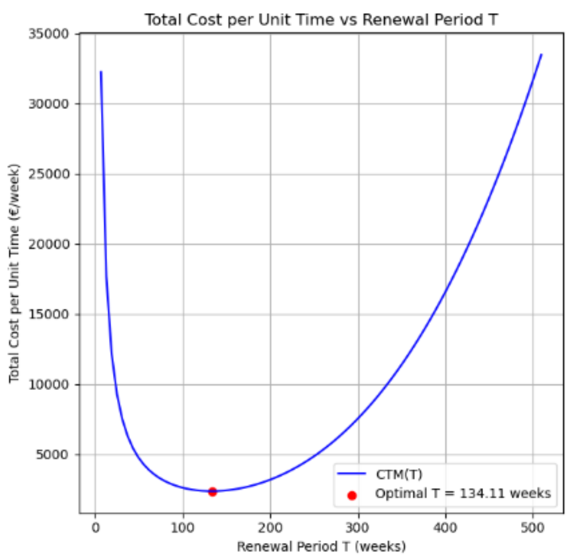

Figure 2. Average Total cost per time unit (CTM) as a Function of Renewal Period T.

Table 3. The obtained optimal renewal period and the corresponding minimum total expected cost per time unit.

T(weeks)*	*CTM*(€/week)*
134	2360

For this considered situation, the minimum required 80% FCOR has been found satisfied for renewal periods ranging between T_1 = 7 weeks and T_2 = 509 weeks as illustrate by figure 3.

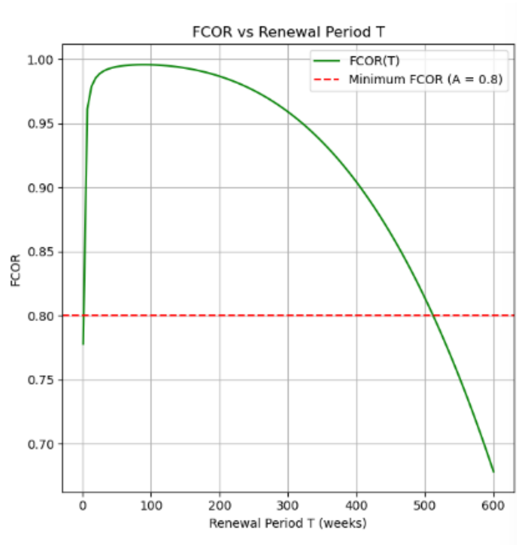

Figure 3. Full Capacity Operating Rate (FCOR) as a function of the renewal period T.

3.2 Sensitivity study

This section examines how variations in critical input parameters impact the optimal maintenance strategy (renewal period *T**) and the associated average total cost rate (*CTM**). Calculations have been performed for two key factors: the average cooling duration *Dcl* and the gearbox reliability through the scale parameter μ of the Weibull distribution associated with the times between overheating events.

Table 4 below shows that since it takes more time to cool the gearbox each time it overheats, the optimal strategy recommends replacing the gearbox sooner (decrease T*). This is consistent with the fact that longer cooling times reduce the Full Capacity Operating Rate (FCOR) of the wind turbine, requiring more frequent replacements to maintain the required 80% availability threshold.

Table 4. Effect of the variation of the average cooling duration of the gearbox

Dcl (hours)	*T*(weeks)*	*CTM*(€/week)*
15	146	2144
25	134	2360
35	122	2531
45	115	2671

As shown by table 5 below, for more reliable gearboxes with less frequent overheating events (increasing MTBO), the optimal maintenance strategy suggests that renewals be performed less frequently (increasing T*).

Table 5. Effect of the variation of the reliability of the gearbox

μ	*MTBO*	*T*(weeks)*	*CTM*(€/week)*
50	45	67	4712
100	90	134	2360
200	181	267	1181

4. Conclusion

This study presented an analytical model to optimize the gearbox renewal period for wind turbines, addressing the trade-off between maintenance costs and operational efficiency. By incorporating a Full Capacity Operating Rate (FCOR) constraint, the model ensures that production losses are minimized while maintaining an effective maintenance strategy. The findings provide valuable insights into the impact of gearbox reliability and production loss costs on decision-making for wind turbine maintenance.

Through extensive testing and sensitivity analysis, the model demonstrated its robustness in adapting to various operational scenarios. The results highlight the importance of a model- and data-driven approach in determining optimal maintenance schedules, reducing reliance on subjective assessments by maintenance crews.

Future research could explore several potential extensions to this work. First, integrating real-time condition monitoring data with machine learning techniques could enhance the predictive capabilities of the model, leading to more dynamic and adaptive maintenance strategies. Additionally, extending the model to account for multiple interacting components within the wind turbine system could provide a more comprehensive maintenance framework. Finally, applying the methodology to other renewable energy infrastructures could further validate its effectiveness and broaden its practical applications.

By refining maintenance strategies through optimization techniques, this study contributes to improving the reliability and economic efficiency of wind farm operations, ultimately supporting the broader goal of sustainable energy production.

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Biographies

Yazid AAFIF is a 3rd year Ph.D. student in Industrial Engineering at the University of Lorraine, Metz, France, specializing in the optimization of maintenance strategies for wind turbines. He holds both a master's and an engineering degree in the field. His research bridges mathematical modeling and data analytics to enhance the reliability and cost-efficiency of wind energy systems.

Sofiene DELLAGI is a full Professor in Industrial Engineering. He received his Ph.D. degree in Industrial Engineering from the University of Lorraine, France. He has been an Associate Professor in Industrial Engineering with the University of Lorraine since 2008, and director of LGIPM Laboratory, since 2024. His research contributions include the publication of several articles and a book. His main expertise and research interests include systems reliability and maintenance, and production management. He has been the Co-Editor of a special issue of the International Journal of Production Research in 2008.

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Lahcen MIFDAL holds a Ph.D. in Engineering Sciences from the University of Lorraine, a Research master's degree in design, industrialization, and innovation, a professional master's degree in industrial systems engineering, an AFAV certification in Value Analysis, and an APICS certification in BASICS of Supply Chain Management, Dr. MIFDAL began his professional career in 2012 at the École Polytechnique of Agadir as a full-time lecturer. Being an ambitious, dynamic, autonomous, methodical, and cooperative individual, he was appointed Head of the Industrial Engineering program in 2013 and Quality Manager in 2015. Since the beginning of his career and to this day, Dr. MIFDAL has remained deeply committed to teaching. Among the subjects he teaches are maintenance management, production management, and systems reliability. In addition to teaching, Mr. MIFDAL is the author of several scientific works and has supervised many graduation projects.

Jérémie SCHUTZ is an Associate Professor in Industrial Engineering at the University of Lorraine, where he also serves as Head of the Mechanical Technology Department at UFR MIM. He holds a Ph.D. in Industrial Engineering from Paul Verlaine University (Metz), with a doctoral thesis focused on optimizing operational and maintenance plans using prognostic approaches, particularly in naval applications. Since joining the University of Lorraine in 2010, Dr. Schutz has taken on several leadership roles, including director of the COSLI professional license programs in Metz and Tunis. His research and teaching center on maintenance strategy optimization, reliability engineering, and production systems management. An active researcher, he has published extensively in high-impact journals such as Computers & Industrial Engineering and Journal of Intelligent Manufacturing, with contributions on maintenance for leased equipment, adaptive failure laws, and reliability modeling. He also regularly serves as a reviewer for academic journals and international conferences in the field of industrial systems.