OPTIMIZING LIFETIME STRATEGIES:
HOW CAN MAST, SCADA DATA, AND DIGITALIZATION MAKE THE DIFFERENCE?

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ABSTRACT

Wind assets valuation is playing a key role for a successful business model. Evaluating the remaining useful life of operating wind assets is the basis for creating multiple economic scenarios and for choosing the one that meets company's goals and mission.

While the upcoming IEC 61400-28 standard will support the industry with defining lifetime extension best practices, it will also focus on ensuring safety of the operating wind assets. Accurate calculation of remaining useful life requires both analytical and practical analysis, for which various input data are valuable. After conducting lifetime evaluations over more than 25 GW worldwide, UL analyzed results of these calculations depending on the available input data at site.

The impact of the number of years available, the minimum number of variables to be considered and the comparison with other sources of information, such as wind measurement inputs based on met mast / RSD is shared. On average, remaining Useful Life can vary 5 years and uncertainties can reduce on two or three-fold depending on the availability of some data, and consequently an emphasis is given on how it can be a game changer for owners and operators to define the most relevant strategy for their operational asset complying with their safety and sustainability goals as well as their ESG commitment.

Keywords:
Lifetime extension, uncertainties, risks, asset management

1. INTRODUCTION

1.1 OBJECTIVE

This article aims to analyze the impact on the quantity and quality of data to offer accurate lifetime forecast for wind turbines, through a comprehensive assessment of real cases all over Europe, and to emphasize on how this kind of studies will be critical for Brazilian wind park owners to maintain competitiveness.

1.2 RELEVANCE FOR BRAZILIAN INDUSTRY

Brazil has gone through an exponential growth in wind power industry since first auctions started in 2009 exclusively for wind energy. Those first auctioned parks are now more than a decade old, which means that they are exceeding half of expected lifetime. Owners and operators aim to ensure the long-term performance and reliability of wind turbines, consequently, diminishing operational costs as much as possible, to achieve this, it is necessary to account with the proper studies that provide meaningful insights for decision makers. Lifetime evaluation, encompassing the comprehensive assessment of wind turbine components, structural integrity, and inspection strategies, will play a paramount role in maximizing energy production, minimizing downtime, and optimizing the economic viability of wind power projects.

This article shows the impact of data availability through a comprehensive analysis of European experience in aging wind parks, this experience will provide relevant insights for the Brazilian wind industry. The first topics offer a brief technical base of lifetime evaluation method calculation which can be applied to any wind park in operation, followed by a comparative analysis of diverse scenarios in which different data sets were available. After this, an uncertainty calculation shows the impacts on data availability for critical wind turbine components, to end with main conclusions and final remarks.

1.3 LIFETIME EVALUATION BASIS

Lifetime evaluation for wind turbines refers to the comprehensive assessment of various factors that impact the performance, durability, and operational lifespan of these renewable energy systems. It involves the systematic examination of key components such as blades, gearbox, generator, control systems, and support structures to determine their condition and potential for deterioration over time. Through a combination of data analysis, inspections and monitoring, lifetime evaluation aims to identify any potential issues, defects, or weaknesses that could affect the efficiency, reliability, and safety of wind turbines throughout their operational lifespan. By proactively assessing and addressing these factors, operators can optimize the energy output, minimize downtime, and extend the useful life of wind turbines, ultimately improving the overall sustainability and economic viability of wind power projects.

2. LIFETIME EVALUATION ANALYSIS ASPECTS

2.1 MAIN INPUTS

Lifetime evaluation is a flexible analysis that may adapt to the available data. Owners and operators may hold a diverse quantity and quality of data sets, depending on several factors, such as: wind turbine manufacturer, previous development, wind park age, data collection software, available met masts, among others. The following items divide the three main data sources to perform lifetime evaluation analysis:

- **Site related:** Topography, layout, complexity, obstacles, Site Values for Load Calculation
- **Turbine Related:** Type certificate, power curves, independent aeroelastic model, etc. for the calculation of design and site-specific loads
- **Operational Information:** SCADA, logs, inspection, maintenance

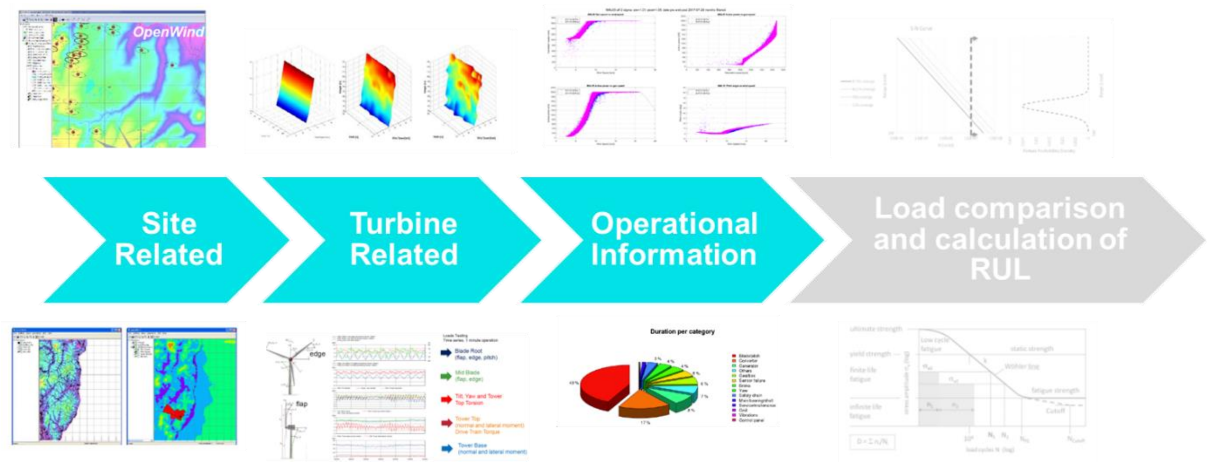

Figure 1 Possible dataset for LTE analysis

2.2 MAIN UNCERTAINTIES

All of LTE variables play a relevant role in accurate calculation. However, two main variables are highly sensitive to reduce uncertainties:

- **Wind speeds:** Due to physics characteristics of wind power output, wind speed has traditionally been a critical sensible variable for all forecasts, as wind power is directly proportional to the cube of wind speed, which means that small changes in wind speed have significant impacts on power output.
- **Turbulence:** Refers to the irregular fluctuations in wind speed and direction, it can have a significant impact on the structural integrity and fatigue life of wind turbine components. High turbulence can accelerate wear and tear, leading to premature failures and reduced life expectancy of the turbine.

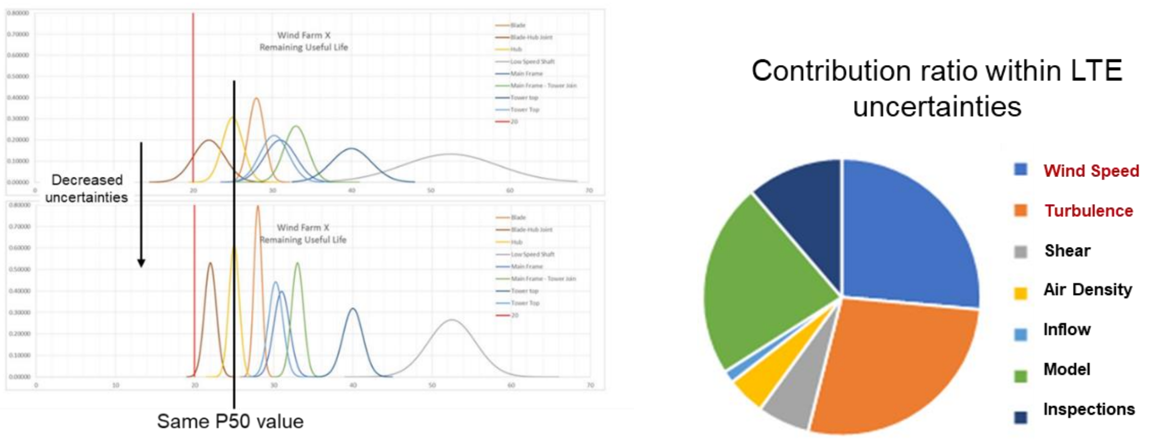

Figure 2 Model sensitiveness to several variables

3. MÉTODO DO ESTUDO

3.1 CASE STUDIES

As the study objective is to emphasize the relevance of data quality and quantity for lifetime extension, regardless of wind park location, 12 wind farms across Europe were selected. As seen in the table and figure below, the locations varied considerably, which established a wind speed, turbulence, layout, and overall characteristics diversity to the study. The turbine models were considered the same for all wind parks in order to focus on wind data sensitivity and avoid any bias by other factors. For each wind park, 4 scenarios of data were applied, as described in the following topic.

Table 1 Analyzed wind parks

Project Name	Country	Capacity (MW)	Mean Wind Speed Affected Wakes (m/s)	Effective turbulence Intensity @15m/s (%)
WF1	Spain	10	5.6	13.98
WF2	Italy	42	7.5	14.56
WF3	Italy	30	7.1	15.42
WF4	Italy	16	7.0	14.84
WF5	Germany	24	6.0	15.05
WF6	France	12	6.1	13.60
WF7	Italy	66	6.2	16.62
WF8	Italy	56	6.5	14.25
WF9	UK	9	7.9	15.31
WF10	Spain	5	7.1	15.63
WF11	Italy	23	6.4	18.96
WF12	Germany	6	6.7	18.02

Figure 3 Wind parks location

3.2 SCENARIO DEFINITION

The following scenario configuration was defined by characteristics of datasets commonly provided by wind industry players to perform such studies. The reason to perform lifetime extension studies may vary, ranging from M&A due diligence activities to O&M strategies such as repowering or revamping actions. It is expected that not always a complete data set is available, either because there is no access, or it is not being produced. The scenarios presented below aim to cover such data availability situations.

1. Mesoscale wind model (no further inputs)
2. Mesoscale wind model and O&M reports (with production and availability)
3. Mesoscale, O&M reports and 10-min SCADA data (average wind speed mean values and standard deviations, wind direction)
4. Mesoscale, O&M reports, 10-min SCADA data (only average wind speed) and high-quality on-site measurements (mast)

Table 2 Scenarios characteristics

Scenario	Wind speed correction	Shear	Wind speed distribution	Effective Turbulence Intensity at 15 m/s	Wind direction
1	No	Mesoscale	Mesoscale	Mesoscale	Mesoscale
2	Yes	Mesoscale	Mesoscale + O&M	Mesoscale + O&M	Mesoscale + O&M
3	Yes	Mesoscale	Mesoscale + O&M + SCADA data	Mesoscale + O&M + SCADA data	Mesoscale + O&M + SCADA data(wind vane)
4	Yes	On-site Mast	Mesoscale + O&M + SCADA data + On-site Mast	Mesoscale + O&M + SCADA data + On-site Mast	Mesoscale + O&M + SCADA data + On-site Mast

3.3 LONG TERM CORRECTION

Prior to calculate the lifetime extension, a long-term correction for the wind model must be applied. This is performed by using SCADA data, which is also used to understand turbine behavior over the years, particularly any previous condition on the equipment. Depending on quality and quantity of data a minimum of 5 years of consistent data should be needed, considering 7-8 years a best-case scenario for results quality.

3.4 AEROELASTIC MODELS

Aeroelastic models for wind turbines are mathematical representations or simulations that combine the principles of aerodynamics and structural dynamics to study the interactions between the wind and the turbine structure. These models are used to analyze and predict the behavior of wind turbines under various operating conditions, including normal operation, extreme weather events, and design considerations. Aeroelastic models consider the following key factors:

1. **Aerodynamics:** The interaction between the wind and the turbine blades is crucial for understanding how the turbine captures energy. The aerodynamic model considers factors such as wind speed, air density, angle of attack, and lift and drag forces acting on the blades.
2. **Structural Dynamics:** The response of the wind turbine structure to aerodynamic forces is modeled using principles of structural mechanics. This includes the dynamic behavior of the rotor, tower, and other components under various loads, such as gravity, wind, and turbulence.
3. **Control Systems:** Aeroelastic models also incorporate the control algorithms and systems used to regulate the operation of wind turbines. These systems adjust parameters such as blade pitch and generator torque to optimize energy capture and ensure the turbine operates within safe limits.

By combining these elements, aeroelastic models can provide valuable insights into the performance, stability, and reliability of wind turbines. They help engineers evaluate design choices, assess the impact of environmental conditions, and optimize turbine operation for maximum energy production and structural integrity.

Such models can be implemented using various techniques, ranging from simplified linear models to more complex nonlinear simulations. These models are typically validated and calibrated using real-world measurements from operational wind turbines and wind tunnel experiments to ensure accuracy and reliability.

3.5 MAIN ASSUMPTIONS

- Loads analysis based on independent aeroelastic models (IAM)
- UL4143 standard / state-of-the-art industry practices / upcoming IEC 61400-28
- Turbine Related input data: same IAM for all projects
- Multidirectional analysis: 84 sectors
- Focus on the most critical / limiting structural components: For 80% of UL fleet analyzed these were the most limiting components (> 26 GW):
    - Blade Root, Composite
    - Blade Root, Joint
    - Hub

  \+ Tower Bottom (Additional component)
- Load uncertainties are based on:
    - wind conditions, IAM, inspections
    - sensitivity load analysis per wind parameter and structural component
    - quadratic sum of each contribution that are considered independent

Component	Station
1. Blade root, Composite	BRMx10
2. Blade root, Joint	BRMx5
3. Hub	BRMx8
4. Hub-Shaft joint	HRMyz5
5. Low speed shaft	HRMyz8
6. Main Frame, Casting	HFMyz8
7. Main Frame, Welded	HFMyz5
8. Main frame- Tower joint	TTMxy5
9. Tower top	TTMxy5
10. Tower bottom	TBMxy5

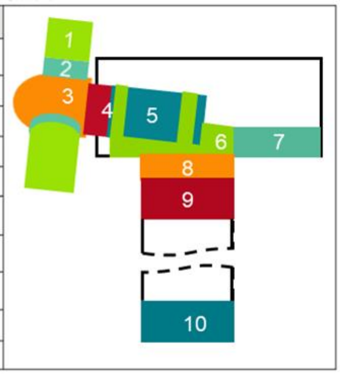

Figure 4 Critical wind turbine parts considered

4. RESULTS

4.1 MAIN VALUES AND DISCUSSION

Blade Root, Composite: The following image shows that remaining useful life spans 32 to 41 years for all scenarios, at 50% of probabilities of exceedance. Results showed consistency as the standard deviation was 5% as average at 50% the probability of exceeding the remaining Useful Life values between each scenario.

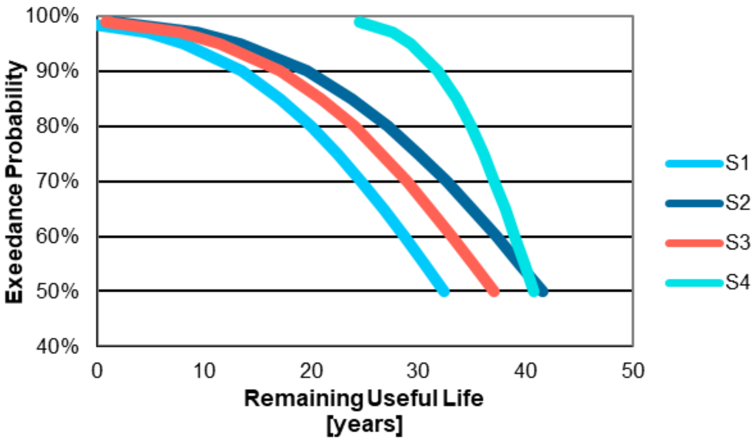

Figure 5 Exceedance Probability of RUL - Blade root, Composite

The tables below depict the uncertainties levels difference among main parameters when considering the different dataset scenarios. Uncertainties can increase from 9.62% to 30.27% for wind shear, and from 2.7% to 10.3% for wind speed. As stated previously, particularly wind speed is a critical value to provide accurate results due to its high sensitivity in simulations and calculations.

Table 3 Main wind characteristics variations

Parameter	Design	Scenario 1 Mesoscale	Scenario 2 O&M report	Scenario 3 SCADA	Scenario 4 On-site
Wind speed	10.0	7.14	6.22	6.1	6.07
TI at 15 m/s	17.97	15.43	14.87	20.21	16.38
Shear	0.20	0.11	0.11	0.1	0.04
Air Density	1225	1.13	1.13	1.13	1.13
Inflow Angle	8.00	-0.16	-0.16	-0.16	-0.17

Table 4 Uncertainty levels

Parameter	Scenario 1 Mesoscale	Scenario 2 O&M report	Scenario 3 SCADA	Scenario 4 On-site
Wind speed	10.30%	5.33%	4.63%	2.76%
Effective TI at 15 m/s	30.27%	30.27%	22.85%	8.50%
Shear	30.27%	30.27%	30.27%	9.62%
Air density	6.41%	6.41%	5.06%	3.51%
Inflow Angle	5.48%	5.48%	2.45%	2.45%

Blade Root, Composite: Life expectancy values trend shows higher values for the scenario 4 (with on-site measurements). Lowest uncertainties for scenario 4 (with on-site measurements) lower than 20% when compared to other scenarios which are above 40%.

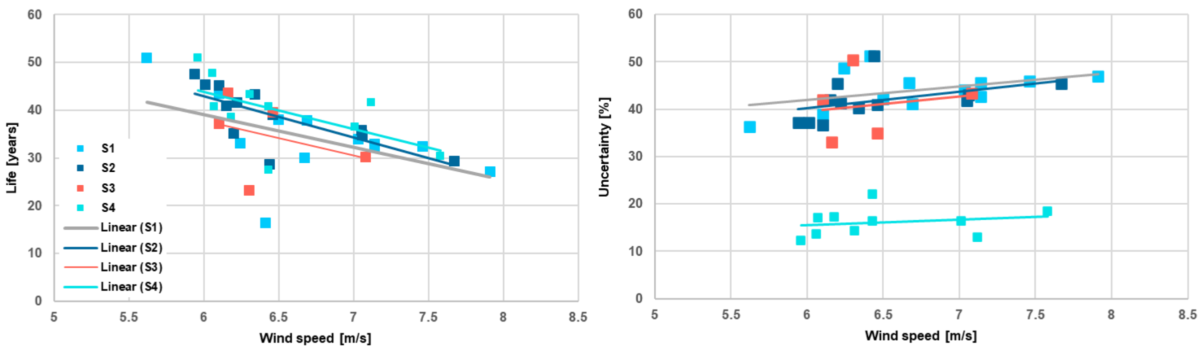

Figure 6 Blade Root, Composite

Blade Root, Joint: Life expectancy values trend shows higher values for the scenario 4 (with on-site measurements). Lowest uncertainties for scenario 4 (with on-site measurements) lower than 10% when compared to other scenarios which are above 20%.

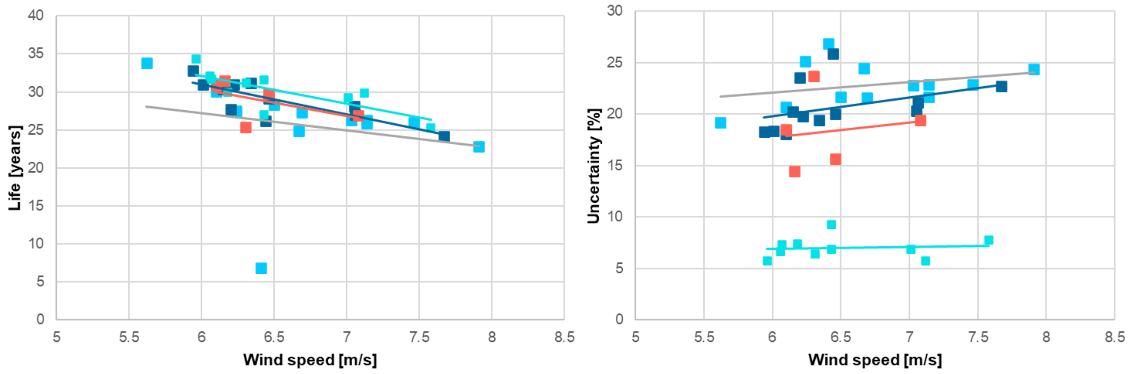

Figure 7 Blade Root, Joint

Hub: Life expectancy values trend shows higher values for the scenario 4 (with on-site measurements). Lowest uncertainties for scenario 4 (with on-site measurements) lower than 15% when compared to other scenarios which are above 35%.

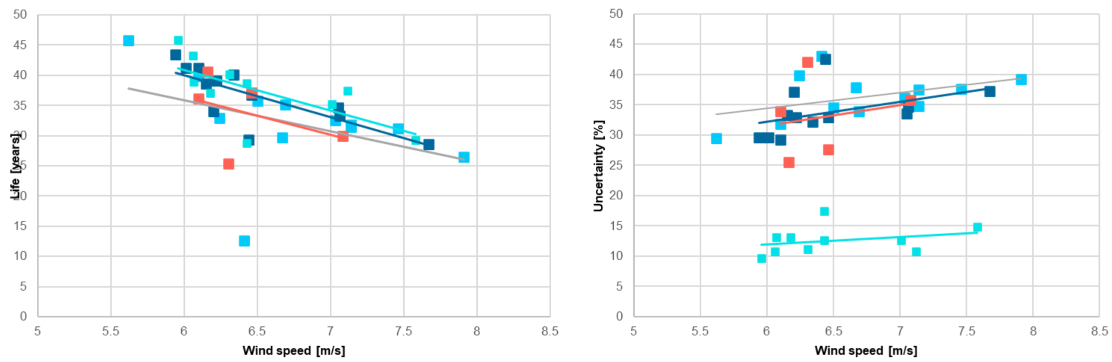

Figure 8 Hub

Tower Bottom: Life expectancy in this case is provided only for calculations, as it is intended that is a much stronger structural turbine component. This analysis is given specially to understand the sensibility difference between Turbulence and Wind Speed. Sensibility to Turbulence Intensity much higher than to Wind speed. Lowest uncertainties for scenario 4 (with met mast). However, in some cases, tower bottom may also be impacted by other factors and its life expectancy could be drastically reduced.

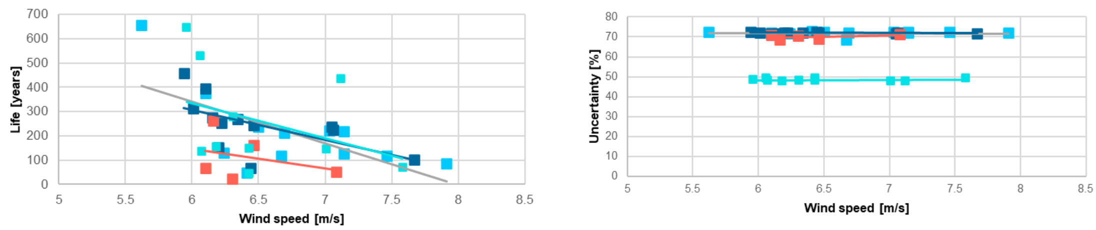

Figure 9 Tower Bottom / Wind Speed

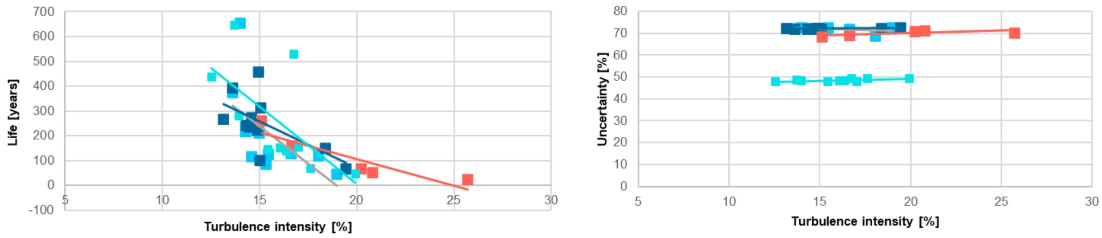

Figure 10 Tower Bottom / Turbulence

5. FINAL REMARKS

- The study shows that the scenarios with less data available and without on-site measurements lead to more conservative results which means that lifetime expectations, especially for blades, can be underestimated. On the other hand, by using a more complete datasets, components lifetime can be fully harnessed, while still evaluating its risks. This gap may vary approximately 5 years difference between scenarios, as seen in the previous graphs.
- SCADA and Mesoscale scenario provide the most conservative results in some cases. Which can be relevant depending on the wind farm age and the operator approach and risks perception. In addition, without using SCADA it will be impossible to understand relevant events that may have affected fatigue conditions for the wind turbine.
- In critical components, blades and hub, uncertainties dropped by a half or a third. This is crucial when interpreting the results and to roll out O&M activities such as future inspections schedules or repowering options, thus, it is possible to perform more accurate OPEX estimates. This study also provides insights of uncertainties levels for LTE screenings for financing Due Diligence or M&A processes.
- Brazilian turbine fleet is ageing, therefore, it is relevant to perform similar studies considering Wind Parks with COD prior to 2010 approximately, and verify the parameters behavior and trends, to understand if local wind conditions effects in wear and fatigue.

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