Response letter to referee #2:

Manuscript WES-2024-68

Title: Added value of site load measurements in probabilistic lifetime extension: a Lillgrund case study

We would like to deeply and truly thank the referee #2 for the very helpful and constructive comments. The views this referee kindly shared helped us gain clarity on how any reader would grasp the research idea and resulted in big improvements in our presentation.

The major and minor comments from referee #2 (black texts) are answered in the current response letter (blue text). Additionally, comprehensive comments were kindly opened by the reviewer in the .pdf version of the paper. This .pdf file is attached to the current letter with responses to all open comments in the same file. All comments are considered and addressed and/or responded[1]

Major Comments

- Scenario Clarity and Consistency: In the introduction, 3 scenarios are introduced. The scenarios should be clearly and consistently defined throughout the paper. A table or flow chart summarizing the scenarios, data sources, and methods would improve clarity. For example, group three of the simulations is used as scenario 2. Renaming the simulation groups to e.g. A, B, C might also help. The scenarios should be extended to the common and relevant scenario where the original aeroelastic simulation model is not available, and a generic simulation model must be utilized (as in this paper).

    - This comment was very helpful for improving the clarity of the paper. Thank you very much. Figure 1 is now added. We also have now pointed out the generic model availability in both the flow chart (fig. 1) and the text (introduction bullet points: line #30 to #40 in the updated paper).

- Scenario 2 Not Fully Developed: While three data availability scenarios are introduced, only scenarios 1 and 3 are fully analyzed. Scenario 2 — using measured turbulence as input to simulations — is mentioned but not developed beyond model validation. Including a full assessment under Scenario 2 would strengthen the comparison and provide a more complete picture of the trade-offs between turbulence-based and response-based approaches. Then you could directly compare what the simulation model predicts, and you can evaluate the difference between the measurements and simulations and better judge the uncertainty coming from the generic simulation model. I see this as optional, given the big effort it would take, and it can be examined to some extent considering the next point:

    - Thank you very much for your comment. We do agree with your statement regarding the great impact such a comparison can have on this work. However, there were two limitations due to which we did not go for full site-specific simulations using SCADA data as input.

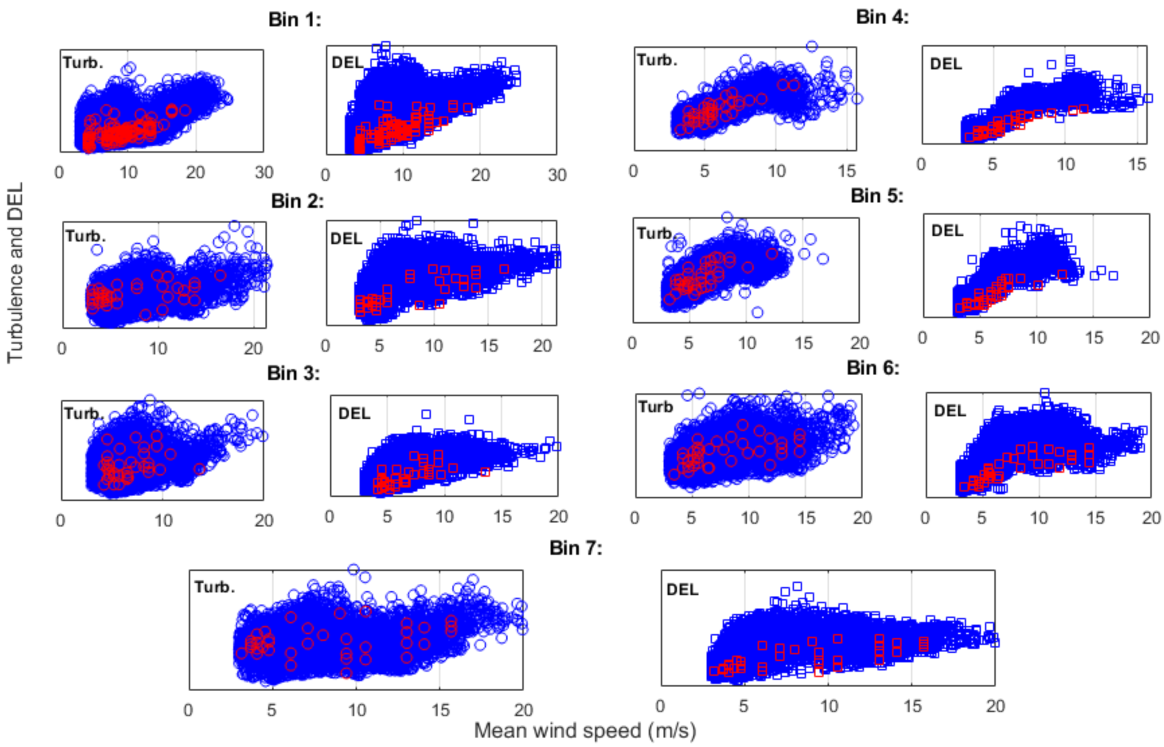
[1] Except for a few for which the data is unfortunately no longer accessible (e.g. power curve.).

First, unfortunately the accuracy of measurements (for both the wind speed and turbulence) can be questioned as in some directions the turbulence measured is not the same as the turbine C08 (under study) is experiencing. This is because in some directions there are wakes imposed to C08 which are not occurring in the met-mast location. Additionally, in some wind directions, the turbine is blocking the met-mast, and the met-mast might is exposed to wakes which the turbine is not exposed to.

Second, we only have access to the SCADA for turbine C08, and the power generation data of the other turbines is not in hand, there would be an effect from other turbines (that the turbine is impacted from, but the met mast is not) that can introduce errors/uncertainties.

However, a point is now added to the discussions and will be picked up in future work (using other available case studies).

For more information:
After receiving this comment, we decided to perform the full simulations (with only 6 seeds) to check the possibility of capturing a realistic fatigue load.



For this purpose, we took limited samples after fitting Gaussian mixture models[2] to wind speed and turbulence (joint distribution) and running simulations using samples covering the probability space. Below are the results in all different direction bins:

[2] Zhang, X. and Natarajan, A.: Gaussian mixture model for extreme wind turbulence estimation, Wind Energ. Sci., 7, 2135–2148, https://doi.org/10.5194/wes-7-2135-2022, 2022.

The x axis in figures above represents mean wind speed (in m/s). Even though the samples taken (on the left side) show a good coverage of environmental input data, the resulting fatigue loads are not representative of the DEL space (from the strain-gauge). All these uncertainties show the effectiveness and benefit of having high accuracy wind data measurements and real time updating model. Having such a combination of continuously calibrated models with SCADA and high accuracy real time measurements can add a very high value and show a fourth reliability curve and a more fair comparison between design and site. This is now pointed out in the discussions and will be picked up in future work (using other available case studies).

The mismatches can be due to some of the reasons below:

- The turbine has experienced lower turbulence than measured (due curtailment of the front turbines, difference in the location of the measurements, etc.).

- Yaw misalignments (not considered in the simulations) make the DEL in flapwise direction lower than in simulation.

- The location of measuring turbulence is different from the turbine experiencing a different flow in some directions.

- The generic model used can introduce errors in the load estimations and thus in the 1Hz DELs.

- The simulations may be closer to reality than the measurements are due to strain-gauge loss of calibrations or errors.

* Uncertainty from Generic Simulation Model: The use of a generic aeroelastic model introduces significant uncertainty. The paper should more thoroughly discuss the limitations of this model and how they may affect the results. A sensitivity analysis or a more detailed analysis (e.g., statistical plots) would help quantify this uncertainty.

We have added references and discussions (lines #460-465 and #508-511) based on this comment.

As there is already previous work dedicated to sensitivity assessment of fatigue loads to model parameters[3] , we decided to refer to that work and add some discussions regarding this important factor. As the generic model structural parameters are given by the OEM and only the controller is adapted (tunned DTU 10MW controller), such discussions could be narrowed down to the yaw misalignment effect in the current work. However, the effect of such uncertainties in lifetime extension assessment (sensitivity of the model errors to environmental conditions), could be different and we have suggested continued research in future on this matter (line # 508).

[3] Robertson, A. N., Shaler, K., Sethuraman, L., and Jonkman, J.: Sensitivity analysis of the effect of wind characteristics and turbine properties on wind turbine loads, Wind Energ. Sci., 4, 479–513, https://doi.org/10.5194/wes-4-479-2019, 2019.

Minor Comments:

- Missing Reference to Lifetime Extension Guidelines: The paper does not reference any established lifetime extension verification guidelines such as DNV-ST-0262. Including such references would provide context and help position the study within the current state-of-the-art.
  - Thank you for your comment. The reference to this standard is added now.
- Extrapolation Justification (L71): The authors state that the best method for extrapolating fatigue loads remains elusive yet proceed with a specific approach. Why was this method chosen despite the uncertainty?
  - Thank you for sharing your question. an explanation provided for what has been done in connection with prev. work: The current work presents a procedure capturing multimodality of fatigue load data—as demonstrated to be effective in 'X'—and extrapolates it over the full assessment duration.
- Language and Grammar: The manuscript would benefit from a language review to improve clarity and readability.
  - Proofreading and polishing of the final text is done now. Thank you for including the editorial comments.
- Explanation of Aeroelastic Model: More detail is needed on the aeroelastic model used, including assumptions (it seems that it is an onshore model), controller implementation.
  - Model is presented in more detail now both in the relevant subsection (2.3.2) and the discussion (effects of the specifics on the results are also discussed through lines #460-465).
- Flowchart Suggestion: A visual representation of the analysis process—from data collection to reliability assessment—would greatly aid reader understanding.
  - Included in fig. 1 now.
- DEL Distribution Sensitivity: The quality of the DEL_lifetime estimate depends heavily on the fitted DEL_10min distribution. Please discuss how well the chosen distribution fits the data and whether alternatives were tested.
  - Gaussian mixture model was also tested as another common mixture model (only bimodal distributions were considered due to the shape of pdf).
- Digital Twin: The term digital twin is used sometimes in the paper. Please clarify whether you consider the aeroelastic simulation model as digital twin and if so, what makes it a digital twin.
  - No, we do not have a digital twin in hand. There is now a more detailed description of this word both in the ending lines of abstract and conclusion:
  - '... accurate environmental and load coupled with accurate models updating in real time with load measurements (digital twins)