

## **Lifetime reassessment of offshore wind turbines considering different operating conditions using Kriging meta-models – Response to reviewers' comments:**

We want to thank both reviewers for their time and effort in reviewing our article and their constructive feedback that helped us to improve the quality of our paper.

In the following, you can find our answers to the comments. Here, the line numbers in the reviewers' comments refer to the first preprint version (initial submission) whereas the line numbers in our answers refer to the revised version of the paper. The edits in the manuscripts are highlighted in magenta for Reviewer 1 and in blue for Reviewer 2.

For your information, in the period between submission and review, the paper was professionally proofread. As a result, some words and, in some cases, sentence structures have changed, but the content has remained unchanged.

### **Reviewer 1:** (marked magenta in the manuscript)

- 1. In the abstract, lifetime reassessment is performed using three different models. It is worth adding in the abstract itself, the quantitative comparison among the three different methods.*

Thank you very much for this comment. To make the quantitative comparison of the three different methods clearer in the abstract, we added a sentence in lines 11 to 13 explaining how the three methods are compared with each other:

“The three methods are compared with regard to the accuracy of their overall lifetime predictions and the computational effort required to make the lifetime predictions.”

- 2. In the abstract, the author can add their insights on high level takeaways and choices among three different methods.*

You are right. Currently, the abstract is very general on this point. We therefore added more detailed results to the abstract in lines 13 to 18 and reworded the existing sentences slightly to clarify the high-level takeaways and choices among the three different methods:

“The results show that both the IEC approach and the meta-model approach can achieve good lifetime prediction accuracy compared with the reference method. However, compared to the reference solution, whilst the IEC-based approach can reduce the computational effort to approximately 20 % of the reference solution's computational effort, the use of meta-models can significantly reduce it to less than 0.5 % of the reference solution's computational effort. The results therefore show that, by using meta-models instead of the original aeroelastic simulation model to reassess the lifetime, the computational effort can be significantly reduced compared to the other two

methods, while maintaining a high approximation quality in the prediction of the lifetime fatigue loads.”

3. *In the literature review, there are significant number of references are mentioned in the manuscript, but there is no clear description on the gap in the existing literature and how it is addressing in the current manuscript. It is value added to clearly bring this into the manuscript.*

Thank you for this comment. To clarify the research gap, we added a sentence in lines 78 to 80 which summarises the two research gaps in the literature after the overview of existing research on the lifetime reassessment of (offshore) wind turbines using meta-models.

“These two gaps in literature regarding lifetime reassessment of (offshore) wind turbines using meta-models – namely, the absence of considering idling conditions and the absence of considering the entire lifetime – will be addressed in this paper.”

4. *I would suggest adding table of comparison with pro’s and con’s among three different methods to easily understand from the manuscript.*

Thank you for this comment. We added a table to the conclusion (Table 7, see below) which compares the three methods in terms of the most important aspects.

**Table 7.** Comparison of the three investigated methods for lifetime reassessment.

critierion	reference	IEC	meta-model
use of original simulation model	yes	yes	no
consideration of all input parameter combinations	yes	no	yes
accuracy	precise calculation of the lifetime DELs, due to the use of the original aero-elastic simulation model and the consideration of all input parameter combinations.	less than 15 % deviation from reference for all three cases ("available" case, "unavailable" case, availability of 90 %). Assuming an availability of 90 %, the deviation is less than 10 % for all internal forces.	less than 10 % deviation from reference for all three cases ("available" case, "unavailable" case, availability of 90 %) with the exception of two internal forces in the "unavailable", idling case. Assuming an availability of 90 %, the deviation is less than 10 % for all internal forces.
computational effort	331,490 simulations	70,000 simulations	1,300 simulations (only simulations for training and test data)

5. *There is typo error in 1<sup>st</sup> paragraph of conclusions ....which served as a reference **solution** and a lifetime calculation*

Thank you for this comment. We corrected that.

6. *General comment: whether the proposed simulation methods are also applicable for onshore wind turbines? Any justifications/comments on the validity might be worth to add as important note in the manuscript.*

Thank you very much for this comment. We assume that the methods presented in the paper can also be applied to onshore wind turbines. However, this would, of course, need to be investigated in future research to be able to make a confident statement on this.

Meta-models for onshore wind turbines are already available for the WindPACT reference turbines (Rinker and Dykes, 2018). We published the meta-models recently as part of a contribution for the Torque 2026 conference (Schmidt et al., 2026a, 2026b). These meta-models could be used to carry out the transferability study directly.

However, it should be noted that – particularly in the case of the IEC approach for onshore wind turbines (IEC 61400-1) – for a simple lifetime reassessment of one onshore wind turbine, significantly fewer combinations of input parameters are simulated than for offshore wind turbines, as the impact of the wave loads is absent. As a result, the computational effort may be reduced only slightly when using meta-models, or may even be higher than with the IEC approach, as the number of simulations required to generate the meta-models could be larger than the number of simulations needed for the lifetime calculation. Nevertheless, the transferability to onshore wind turbines is a point that should be investigated in future work, since, for example, in case of probabilistic lifetime calculations or design optimisations (incorporating design parameters as input parameters), the computational effort increases significantly.

To clarify this point in the manuscript, we added a few sentences in lines 554 to 560, in which we discuss the generalisability of this study's results to onshore wind turbines. The following sentences were added:

“The findings are also expected to be transferable to onshore wind turbines. In this case, however, for a simple lifetime calculation of one onshore wind turbine, the computational effort when using meta-models may be only slightly reduced or even increased compared to the approach according to IEC 61400-1, as significantly fewer aeroelastic simulations are generally carried out for lifetime calculations of onshore wind turbines. Nevertheless, the transferability of the findings of this work to onshore wind turbines is a point that should be investigated in future work, too, since, for example, in the case of probabilistic lifetime calculations or design optimisations (incorporating design parameters as input parameters), the computational effort increases significantly.”

**Reviewer 2:** (marked blue in the manuscript)

### Specific Comments

1. *In Section 2.3, the authors use a Monte Carlo step-by-step sizing approach to determine where the lifetime DEL converges, thereby avoiding the need to run the full set of 1,314,900 simulations. However, the manuscript does not clearly define the criterion used to determine convergence. What criterion was used to decide that the lifetime DEL had converged? This should be clearly defined.*

Thank you for this comment. We defined as a criterion for convergence that the lifetime DELs have converged as soon as the deviation of the lifetime DELs from the lifetime DELs determined using the maximum number of simulations is less than 0.5 %. With a maximum deviation of 0.5 %, it can be assumed that a level of accuracy has been achieved which is, in any case, lower than other uncertainties arising within the calculations of the lifetime DELs. To clarify this point in the paper, we slightly reworded the corresponding sentence in the paper and added the before mentioned argument with the level of accuracy in lines 220 to 223:

“Convergence is assumed if the deviation of the corresponding lifetime DEL is less than 0.5 % compared to the lifetime DEL determined with the maximum number of simulations investigated. It is assumed that with a convergence criterion of a maximum deviation of 0.5 %, a level of accuracy has been achieved which is, in any case, lower than other uncertainties arising within the calculations of the lifetime DELs.”

2. *In Lines 324–330,: I believe the inclusion of idling conditions is one of the key selling points of this paper. Therefore, a deviation of this magnitude should not be dismissed without further explanation. At the very least, some reasoning or investigation should be provided. For example, if idling conditions were excluded, would the deviation remain similarly large? This issue is particularly important if the proposed method is intended to be applied to cases where idling loads are more influential.*

Thank you very much for this important comment. You are right, the description in the paper is not entirely clear at the moment.

The high deviation of 31 % from the reference solution applies only to  $M_{x,Root,lifetime}$  under idling conditions (“unavailable” case). If only normal operation is considered, this high deviation is irrelevant. This becomes clear from a previous study we conducted (Schmidt et al., 2023), in which the lifetime DELs were determined only for normal operation. Here, for  $M_{x,Root,lifetime}$  predicted by the meta-model, the deviation from the reference solution was less than 1 %. If idling is taken into account as in the current study, the large deviation for the “unavailable” case (only idling) is certainly irrelevant for the wind turbine investigated in this study, as the internal forces in idling conditions for  $M_{x,Root}$  are significantly smaller than the operating loads. This can be seen in the figure below (Schmidt et al., 2025a) in which the short-term DELs for the same wind turbine are compared between normal operation and idling. Due to the fact that  $M_{x,Root,DEL}$  is significantly smaller during idling compared to normal operation, the effect of idling on the overall lifetime DEL when considering a typical availability of 90 % is

also small (as shown in the current study). Even when the availability varies, the impact of idling on  $M_{x,Root,lifetime}$  remains small as shown in Fig. 8 in this paper.

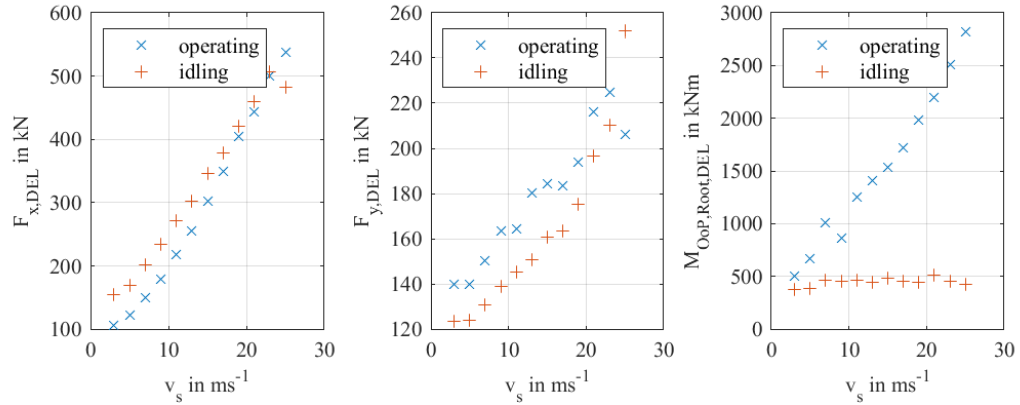


Figure 1: Comparison of the internal forces between idling and operating conditions for  $F_{x,DEL}$ ,  $F_{y,DEL}$ , and  $M_{OoP,Root,DEL}$ . Here,  $M_{OoP,Root,DEL}$  is equal to  $M_{x,Root,DEL}$ . Figure by Schmidt et al. (2025a).

However, for other wind turbine types where  $M_{x,Root,DEL}$  under idling conditions is of a similar order of magnitude to that under operating conditions, and where the turbine also idles frequently, the significant deviation in the meta-model's prediction could become a problem. In this case, it would be necessary to investigate more closely where the deviations come from and how they can be reduced.

To clarify this point, we reworded the corresponding paragraph (lines 330 to 341) in the paper to make it clear that, first, the deviation only applies to the “unavailable”, idling case, and second, that the values for  $M_{x,Root,DEL}$  for idling are significantly lower than during normal operation:

“For the meta-model of  $M_{x,Root}$  for idling conditions, it can be assumed that the important effects are not all taken into account in the meta-model. This becomes clear when looking at the predicted short-term DELs of  $M_{x,Root}$  as a function of individual input parameters, e.g., as a function of  $v_s$  or  $T_p$  as shown in Fig. 4. Across the entire wind speed range and also across a large range of the peak period, the meta-model underestimates the short-term DELs calculated by the simulation model. In contrast to the bending moments at the monopile, however, the deviation of  $M_{x,Root,lifetime}$  is significantly higher at approximately 31 % for the “unavailable”, idling case. This is a very large deviation, which is not acceptable at first glance. Nevertheless, for the investigated offshore wind turbine, the values for  $M_{x,Root,DEL}$  under idling conditions are significantly smaller compared to normal operation as shown by Schmidt et al. (2025a). Therefore, for  $M_{x,Root}$ , idling has only a very minor impact on the overall lifetime DEL at 90 % availability of the wind turbine as shown in Table 3. As the focus of this work is not only on idling conditions, the high deviation of  $M_{x,Root,lifetime}$  for the “unavailable” case will not be addressed further in this paper. However, this is an issue that should be investigated more closely in future work, particularly if idling forms the focus of an investigation.”

Additionally, in the conclusions, in lines 546 to 547, we extended the existing statement that these deviations should be investigated in greater detail to make it clear that this

large deviation is particularly critical when the internal forces under idling conditions are of a similar magnitude to those during normal operation and thus have a greater impact on the lifetime of the wind turbine:

“This is particularly important if these internal forces under idling conditions are of a similar magnitude as during normal operation, meaning that idling has a significant impact on the lifetime of the wind turbine.”

3. *In Section 3.3, the authors note that using the mean Kriging prediction is not conservative and then state that using the 65th percentile for normal operation and the 70th percentile for idling leads to conservative lifetime DEL estimates. This is an interesting and useful correction, but the choice of these percentiles appears empirical and case-specific. The manuscript should explain how these percentiles were selected and discuss whether they are expected to generalize to other turbines or sites.*

Thank you for this comment. You are right. The choice of the mentioned percentiles is empirical and case- or turbine-specific.

We assumed that the prediction of the lifetime DELs are conservative if the meta-models predict lifetime DELs that are greater than the lifetime DELs calculated using the reference solution. Since the lifetime DELs are normalised using the reference solution, this means that the predicted lifetime DELs are conservative as soon as the calculated lifetime DELs are larger than 1.

To make this point clearer, we added a description of our criterion for a conservative prediction in lines 451 to 455:

“It is assumed that the predicted lifetime DELs are conservative if the meta-models predict lifetime DELs that are larger than the lifetime DELs calculated using the reference solution. Since the lifetime DELs predicted using the meta-models are normalised using the reference solution, this means that the predicted lifetime DELs are conservative as soon as the normalised predicted lifetime DELs are larger than 1.”

Furthermore, we assume that the results regarding the chosen percentiles (70th percentile for idling and 65th percentile for normal operation) are, in principle, transferable to other turbines or sites. However, the transferability of the chosen percentiles to other turbine types / foundation types / sites is something that should be investigated in future work. To clarify this point, we added a few sentences in the conclusions in lines 549 to 554, in which we discuss the generalisability of this study’s results to other types of wind turbines, other sites, etc. The following sentences were added:

“It is assumed that the results of this study – namely, the suitability and the required computational effort of the use of meta-models for lifetime reassessment as well as the chosen percentiles for a conservative prediction of the lifetime DELs using the meta-models – are, in principle, transferable to other sites, other types of wind turbines and/or other support structures. However, to be able to make a reliable statement on this, the transferability of the findings of this study should be investigated in more detail in future research.”

## Minor Comments

1. *Line 83 contains a typo: “The paper ist structured as follows.” This should be corrected to “The paper is structured as follows.”*
2. *Line 158 contains a double period: “...for the in-plane and out-of-plane bending moments.. For idling...”.*
3. *In Table 2, the range of  $TpTp$  is listed as “0.25–30.25 m.” This should likely be in seconds rather than meters.*

Thank you very much for pointing out these typos. We corrected them all.

## **References used in response to reviewers:**

Rinker, J. and Dykes, K.: WindPACT reference Wind Turbines, National Renewable Energy Laboratory, Golden, Colorado, USA, <https://doi.org/10.2172/1432194>, 2018.

Schmidt, F., Hübler, C., and Rolfes, R.: Lifetime reassessment of offshore wind turbines using meta-models, in: 14<sup>th</sup> International Conference on Applications of Statistics and Probability in Civil Engineering (ICASP14), Dublin, Ireland, 9-13 July 2023, <http://hdl.handle.net/2262/103307> (last access 1 June 2026), 2023.

Schmidt, F., Hübler, C., and Rolfes, R.: Kriging meta-models for damage equivalent load assessment of idling offshore wind turbines, *Wind Energ. Sci.*, 10 3069-3089, <https://doi.org/10.5194/wes-10-3069-2025>, 2025.

Schmidt, F., Krabbe, P., Hübler, C., and Rolfes, R.: An open-access database for meta-models for fatigue calculations of reference turbines. *J. Phys.: Conf. Ser.*, 3224, 072003, <https://doi.org/10.1088/1742-6596/3224/7/072003>, 2026a.

Schmidt, F., Krabbe, P., Hübler, C., and Rolfes, R.: Open-access database for meta-models for fatigue calculations of reference wind turbines, LUIS [data set], <https://doi.org/10.25835/eydp1n12>, 2026b.