Lifetime reassessment of offshore wind turbines using meta-models

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ABSTRACT: At the end of the lifetime of offshore wind turbines, there are various options. One option is to continue operating beyond the theoretical lifetime of the offshore wind turbine. To enable this, first, the remaining lifetime must be determined with a lifetime reassessment. However, the difficulty here is the very high comping time required to determine the remaining lifetime. Possible options for reducing the computing time are, for example, the reduction of load cases or the use of meta-models. In this work, three different methods for lifetime reassessment of offshore wind turbines are investigated and compared to identify differences of the three methods and to find out, whether the use of meta-models for lifetime reassessment is suitable. The three methods are a full lifetime reassessment approach using a Monte Carlo simulation, an approach according to the standard IEC 61400-3 and a meta-model based approach. The results show that it is possible to use meta-models instead of the original aero-elastic simulation model for the lifetime reassessment. The computing time can be signficantly reduced while maintaining a high approximation quality in the prediction of lifetime fatigue loads.

1. INTRODUCTION

Offshore wind turbines are usually designed for 25 years. After this period, there are various options regarding the further use of wind turbines. One option is a so-called lifetime extension, i.e., to continue operating even after the 25 years. However, to continue operating a wind turbine after its theoretical end of life, the remaining lifetime must be determined first. This can be done by a so-called lifetime reassessment. Therefore, the actual lifetime is calculated based on the real occured environmental conditions, e.g., wind speeds at the precise site instead of using past conditions (perhaps, even of a slightly different site) as it is done for the design. However, a lifetime reassessment requires very high computing times due to the large number of simulations. This means that it is hardly possible to do a lifetime calculation with time-domain simulations. Therefore, generally representative load cases, i.e., representative combinations of environmental parameters, are calculated and the resulting damage of this calculations is then extrapolated to the lifetime using the frequency of occurrence of the combinations of the environmental parameters (e.g. Ziegler and Muskulus (2016); Bouty et al. (2017)). However, this method cannot take into account all combinations of environmental parameters that may have occurred. This and additionally the extrapolation to the lifetime make the calculation of the lifetime inaccurate. An alternative option that may reduce these inaccuracies is to use a meta-model as a surrogate of the original aero-elastic simulation model. Due to the significantly reduced computing time of the meta-model, all combinations of the environmental parameters can be calculated, although each calculation is only an approximation compared to the original simulation model. Due to the low computing time of the meta-model, another advantage of using meta-models is that changes during the lifetime of the wind turbine can be taken into account quickly. For example, the lifetime may have to be calculated several times because a new wind farm has been built nearby during the lifetime which changes the wind conditions in the existing wind farm. Another reason could be an adjustment of the controller behaviour of the wind turbine. In these cases, if a meta-model is used, only a new calculation with the meta-model is necessary or (in the second case) a new meta-model needs to be created. In contrast, without a meta-model, it is not possible to re-simulate the complete lifetime with the original simulation model.

Meta-models, such as Kriging, artificial neural networks or polynomial chaos expansion are already used in wind energy e.g., for sensitivity analyses (e.g., Hübler et al. (2017c); Müller et al. (2018)), design optimisation (e.g., Yang et al. (2015); Häfele et al. (2018)) or the prediction of ultimate or fatigue loads (e.g., Dimitrov et al. (2018); Wilkie (2020); Stewart (2016)). However, to the authors' knowledge, a lifetime reassessment using meta-models, whereby a meta-model is used to reassess the lifetime has not yet been investigated.

In this work, three methods for a lifetime reassessment of an offshore wind turbine are investigated and compared: A full lifetime calculation, where a Monte Carlo simulation is used to calculate the lifetime, a lifetime calculation according to the standard IEC 61400-3 (International Electrotechnical Commisson (2019b)) and a lifetime calculation using meta-models. The aim is to identify the differences between the three methods and to find out to what extent meta-models are suitable for the lifetime calculation compared to other methods. The used methods can be used both for the design of an offshore wind turbine and for the lifetime reassessment. Since the aim is to subsequently use the meta-models in the context of a lifetime reassessment, in the following sections, the term lifetime reassessment will be used.

2. METHOD

2.1. *Simulation model and settings*

The areo-elastic time-domain simulations for the investigations in this work are conducted with the aero-hydro-servo-elastic code FASTv8 of the National Renewable Energy Laboratory (Jonkman (2013)). A soil model that enhances the FASTv8 code is considered (Häfele et al. (2016)). As wind turbine model, the NREL 5 MW reference turbine (Jonkman et al. (2009)) with the OC3 monopile and soil (Jonkman and Musial (2010)) is used. For more information regarding the simulation model, the reader is referred to Müller et al. (2021).

Each simulation has a usable simulation length of 600 seconds. Additionally, a "run-in" time of 240 seconds is considered to be discarded to eliminate the effects of the initial transients. According to Hübler et al. (2017a), this additional time should be sufficient for the calculation of fatigue loads for the NREL 5 MW reference turbine on a monopile.

For the simulations, power production operating conditions are assumed. This means that the wind speed ranges between 3 and 25 ms^{-1}. As environmental conditions, statistical distributions for the environmental parameters are used, which were determined by Hübler et al. (2017a) from measurements at the FINO 3 research platform. Five scattering parameters are considered: mean wind speed v_s, turbulence intensity TI, significant wave heigth H_s, wave peak period T_p and wind wave misalignment θ_{mis}. Hübler et al. (2017b), Murcia et al. (2018) and Velarde et al. (2019) identified these parameters as significant in sensitivity analyses.

The simulated loads in the time domain are transformed into short-term damage equivalent loads (DELs) according to Palmgren-Miner rule. The short-term DELs are calculated as follows:

$$S_{eq} = \left(\sum \frac{n_i S_i^m}{N_{ref}} \right)^{\frac{1}{m}}. \quad (1)$$

Here, n_i is the corresponding number of cycles for each Goodman-corrected (Goodman (1899)) load range S_i determined by a rainflow counting. $N_{ref} = 600$ is the number of equivalent cycles for a frequency of 1 Hz for a 600 seconds time series and m is the Wöhler exponent. The Wöhler exponent $m = 3$ is chosen for steel and $m = 10$ for the composite material of the rotor blades.

The lifetime reassessment in this work is carried out for the forces and moments at the monopile at the mudline and for the blade root moments. A list of the considered loads and a description can be found in Table 1.

Table 1: Considered damage equivalent loads

Load	Description
F_x	Shear force at mudline in wind direction
M_y	Overturning moment at mudline in wind direction
F_y	Shear force at mudline perpendicular to the wind direction
M_x	Overturning moment at mudline perpendicular to the wind direction
$M_{x,Root}$	In-plane bending moment at the blade root
$M_{y,Root}$	Out-of-plane bending moment at the blade root

2.2. *Lifetime reassessment*

In this work, three different methods for lifetime reassessment of offshore wind turbines are investigated and compared. The first method is a full lifetime reassessment. This method represents an accurate lifetime calculation and is therefore used as a reference solution within the scope of this work. The second method is a lifetime calculation according to IEC 61400-3 and the third method is a lifetime reassessment using a meta-model. The three methods are compared to identify differences and to find out whether the use of meta-models is suitable for lifetime reassessment. In the following, the three methods are discussed more in detail.

2.2.1. *Full lifetime reassessment*

For the full lifetime reassessment (reference solution) the simulations are carried out using the areo-elastic simulation model and settings described in Section 2.1. Due to the high computing times required to calculate the entire lifetime of an offshore wind turbine, 100,000 simulations were carried out in order to keep the computing effort slightly lower. These 100,000 simulations correspond to approximately 1.9 years of the wind turbine's lifetime, which is considered sufficient for the investigation within the scope of this work. The simulations are created using the Monte Carlo sampling method. The short-term DELs resulting from the 100,000 simulations are then converted into a lifetime DEL using the following equation (Dimitrov et al. (2018)):

$$S_{eq,lifetime} = \left[\sum_{i=1}^{N} [S_{eq}(\mathbf{x}_i)]^m p(\mathbf{x}_i) \right]^{1/m} . \quad (2)$$

Here, $\mathbf{x}_i$ is the ith vector of input variables $[v_s\ TI\ H_s\ T_p\ \theta_{mis}]^T$, N is the number of simulations and $p(\mathbf{x}_i)$ is the probability of occurence of each simulation. Since the Monte Carlo sampling method is used, here, the probability of occurence of each simulation is $p(\mathbf{x}_i) = 1/N$.

2.2.2. *Lifetime reassessment according to the standard IEC 61400-3*

For the lifetime reassessment according to the standard IEC 61400-3 (International Electrotechnical Commisson (2019b)) the input parameters mean wind speed v_s, significant wave heigth H_s and wave peak period T_p must be considered as scattering parameters. Additionally the wind and wave direction can be taken into account. In this work, the wind wave misalignment θ_{mis} is considered instead. This is consistent with the work of Stewart (2016). According to IEC 61400-1 (International Electrotechnical Commisson (2019a)), the 90th percentile of the corresponding probability distribution should be used for the turbulence intensity. Since it is possible that the use of the 90th percentile of the turbulence intensity leads to significantly higher lifetime DELs compared to the other methods used in this work, where the turbulence intensity is considered as a scattering parameter, the mean value for the turbulence intensity is also taken into account. All calculations according to the IEC standard are thus performed once for the 90th percentile and once for the mean value of the turbulence intensity.

Table 2: Considered bin sizes according to IEC 61400-3 and ranges of the input parameters

Input parameter	Bin size	Range
v_s	2 ms^{-1}	3 to 25 ms^{-1}
H_s	0.5 m	0 to 10 m
T_p	0.5 s	0 to 30.5 s
θ_{mis}	30°	−180° to 180°

To create the load case set, the probability distributions of the four input parameters are divided according to the bin sizes given in Table 2 and the probability of occurence is determined for each bin. Then all possible combinations of the parameters are determined and for each combination (bin) the probability of occurence is calculated by multiplying the probabilities of occurence of each of the four parameters. For example, the 16,252th bin $4\ \text{ms}^{-1} \leq v_s \leq 6\ \text{ms}^{-1}$, $1.00\ \text{m} \leq H_s \leq 1.50\ \text{m}$, $6.00\ \text{s} \leq T_p \leq 6.50\ \text{s}$, and $\text{-}75° \leq \theta_{mis} \leq \text{-}45°$ has an occurrence probability of

$$p_{j=16252} = 0.1340 \times 2.2622 \times 0.1232 \times 0.0822 = 3.5576 \times 10^{-4}. \quad (3)$$

If all possible combinations of the four input parameters are considered for the statistical distributions from the FINO 3 research platform (Hübler et al. (2017a)), this results in a number of 175,680 bins. Additionally, according to IEC 61400-3 six 10-minute simulations with different seeds or one 1-hour simulation must be carried out in each bin. In the case of six different seeds, this results in a number of 1,054,080 simulations. The computational effort to conduct this number of simulations is very high. However, by taking into account all possible combinations of the input parameters, i.e., bins, combinations are also considered that do not or only very rarely occur in reality, such as a low wave height in combination with a high wind speed. In order to reduce the computing time, bins with a very low probability of occurence are therefore not considered. For these bins, it can be assumed that the probability of occurence of these bins is so small that the influence on the lifetime of the wind turbine is negligible, even if the damage they cause is high. Only those parameter combinations were taken into account for which the probability of occurence is so high that they occur at least once during the lifetime of the wind turbine, i.e.,

$$p_{min} = \frac{1}{25 \times 365.25 \times 24 \times 6} = 7.6 \times 10^{-7}. \quad (4)$$

By introducing p_{min} as the minimum probability of occurence, the number of relevant bins can be reduced to 14,676, i.e., 88,056 simulations in total. Although the number of bins is significantly reduced, 99.75 % of the load cases that actually occur are still taken into account, i.e., $\sum\{p_j | p_j > p_{min}\} \approx 0.9975$. This shows that the number of bins can be significantly reduced without neglecting significant load cases.

The resulting short-term DELs from the 88,056 simulations are then converted into lifetime DELs using Equation 2. However, in contrast to the full lifetime reassessment, here, $p(\mathbf{x}_i) = \frac{p_j}{6}$ corresponds to the probability of occurrence of each simulation in the jth bin. Here, $\mathbf{x}_i$ represents the input variables $\mathbf{x}_j$ from the jth bin.

2.2.3. *Lifetime reassessment using a meta-model*

As mentioned before, meta-models are increasingly used as surrogate models for aero-elastic simulation models. In this work, a lifetime reassessment will be carried out using a meta-model. The meta-models used in this work are Kriging meta-models created by Müller et al. (2022). The input parameters of the meta-models are the five environmental parameters mentioned in Section 2.1 (v_s, TI, H_s, T_p, θ_{mis}) and the outputs are the short-term DELs summarised in Table 1. Thereby, a separate meta-model was created for each DEL, resulting in six different meta-models. The Kriging meta-model used was created using 8,500 training samples generated with a Halton sequence. As settings, a quadratic basis function and the anisotropic matern 3/2 covariance function were used for the meta-model. For more information regarding the Kriging meta-model, the reader is referred to Müller et al. (2022).

To calculate the lifetime DELs with the meta-model the same 100,000 input parameter combinations used for the full lifetime reassessment described in Section 2.2.1 are used. The short-term DELs returned for the 100,000 input parameter combinations by the meta-models are then converted to lifetime DELs using Equation (2). Here, as in Section 2.2.1, the probability of occurence of each simulation is $p(\mathbf{x}_i) = 1/N$.

3. RESULTS

In Table 3, the normalised lifetime DELs calculated with the described methods are shown. Furthermore, Figure 1 shows the normalised lifetime DELs for $M_{y,lifetime}$, $M_{x,lifetime}$ and $M_{y,Root,lifetime}$ versus the number of simulations used for the calculation of the lifetime DELs. From Table 3, it becomes clear that the deviations of the lifetime DELs between the three different calculation methods are small with less than 10% deviation of the lifetime DELs of the reference solution. It can also be seen that using the calculation method according to IEC 61400-3 when using the 90th percentile for the turbulence intensity leads to a up to 9% higher lifetime DEL compared to the reference solution. This means it leads to a more conservative result compared to the full lifetime reassessment. In contrast, the lifetime DELs, which were calculated according to IEC 61400-3 but with the mean value for the turbulence intensity, are up to 5% below the values for the reference solution for all loads except $F_{y,lifetime}$. The most significant deviations can be seen for $M_{y,Root,lifetime}$ (see also Figure 1, right). This can be explained as the wind loads and thus the turbulence intensity have the greatest influence on the rotor blades in wind direction. For the out-of-plane loads at the rotor blade, however, the turbulence intensity does not have such a major influence, as these loads are primarily influenced by the rotation of the rotor. Also for the loads on the monopile, the influence of the wind loads is not that large because the wave loads also have a significant influence, which means the influence of the turbulence intensity is lower.

The lifetime DELs calculated with the meta-models deviate from the reference solution by only 2% except for $M_{x,lifetime}$ (see Table 3). Thus, the deviation of the lifetime DELs calculated with the meta-models are smaller than the deviations of the lifetime DELs calculated with the method according to IEC 61400-3 for most loads. However, for $M_{x,lifetime}$, the deviation is significantly higher (9%, see also Figure 1, centre). One reason for the larger deviation could be that the used meta-models approximate the different loads with different approximation quality (Müller et al. (2021)). In Müller et al. (2021) it turned out that $M_{x,lifetime}$ is approximated worst by the Kriging meta-model compared to the other loads which is consistent to the results in this work.

Furthermore, Table 3 shows that the meta-model lifetime DELs for almost all loads are below the lifetime DELs of the reference solution. The calculation with the meta-models is thus not conservative. This must be taken into account when using the meta-models for the calculation of lifetime DELs. Possible ways to ensure that the meta-models do not provide results on the uncertain side compared to the original simulation model are, for example, the consideration of safety factors or, as suggested in IEC 61400-1, the use of the 90th percentile for the turbulence intensity instead of considering the entire probability distribution of the turbulence intensity.

When looking at the influence of the number of simulations used for the calculation of the lifetime DELs in Figure 1, it becomes clear that the number of simulations used for the method according to IEC 61400-3 has a large influence on the lifetime DELs of all considered loads. Here, at least 40,000 simulations must be carried out to ensure that the deviation from the reference solution is less than 10% for all loads and the lifetime DEL is reasonably converged ($M_{y,Root,lifetime}$ is the decisive factor). For the meta-models, however, only the 8,500 simulations conducted for the training of the meta-models are relevant, as no more simulations need to be conducted for the determination of the lifetime DEL. Thus, compared to the reference solution, using the IEC 61400-3 calculation method the

Table 3: Normalised calculated lifetime DELs

Load	full lifetime (reference)	IEC 61400-3 90th percentile	IEC 61400-3 mean value	meta-model approach
$F_{x,lifetime}$	1.000	1.022	0.987	0.997
$M_{y,lifetime}$	1.000	1.047	0.967	0.986
$F_{y,lifetime}$	1.000	1.028	1.011	0.988
$M_{x,lifetime}$	1.000	1.002	0.993	0.910
$M_{x,Root,lifetime}$	1.000	1.007	0.998	1.001
$M_{y,Root,lifetime}$	1.000	1.090	0.946	0.999

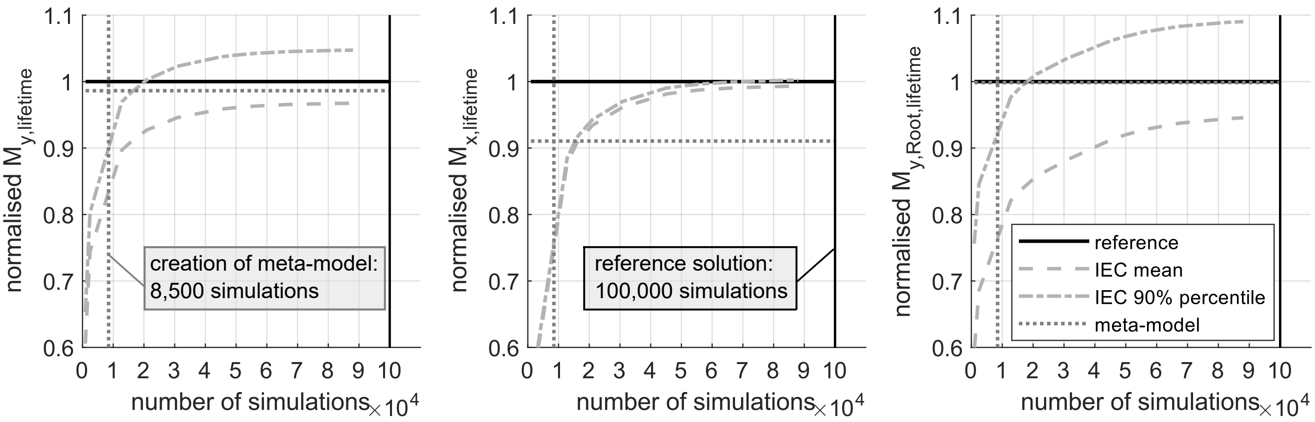

Figure 1: normalised lifetime DELs of the three methods versus the number of simulations used for the calculation of the lifetime DELs. Left: $M_{y,lifetime}$, centre: $M_{x,lifetime}$, right: $M_{x,Root,lifetime}$

computing time can be more than halved and alternatively, when using meta-models, the computing time can be reduced to less than 10% of the computing time for the full lifetime reassessment. These values change to approx. 3% and approx. 0.5% if the reference solution considers 25 years and not only 100,000 simulations. Thereby, as described above and as shown in Figure 1, only a small approximation error arise through the use of the meta-model.

It can be summarised that both the method according to IEC 61400-3 and the meta-model method lead to good results in the lifetime reassessment compared to the reference solution, the full lifetime reassessment. However, it can be said that the computing time of the meta-model method is significantly (approx. 5 times) lower and the deviations of the lifetime DELs from the reference solution are smaller in most cases compared to the method according to IEC 61400-3.

4. CONCLUSIONS

In this work, three different methods for the lifetime reassessment or lifetime calculation have been investigated and compared. The first method is a full lifetime reassessment where a simulation of 1.9 years of a wind turbines' lifetime was conducted using 100.000 simulations. The second method is a lifetime reassessment according to IEC 61400-3 and the third method is a lifetime reassessment using meta-models instead of the original aero-elastic simulation model. The aim was to identify differences between the three methods and to find out to what extent meta-models are suitable for lifetime reassessment in comparison to other methods.

The results show that both, the method according to IEC 61400-3 and the meta-model based approach lead to good results regarding the lifetime reassessment. Nevertheless, the meta-model based approach performs better in terms of the approximation quality and regarding the required computing time. For the meta-model based approach, however, the approximation quality of the meta-model plays a major role. If the approximation quality of the meta-model is not sufficient, the approximation of the lifetime DELs is correspondingly worse.

It can be summarised that the use of meta-models is suitable to conduct a lifetime reassessment, as both a high degree of accuracy and a low computational effort can be achieved. Nevertheless, there are some open points that should be clarified in future work. As mentioned before, the values of the lifetime DELs calculated with the meta-models are in most cases below the lifetime DELs of the full lifetime reassessment. This can lead to a longer remaining lifetime being predicted than actually exists. A possibility to make the lifetime DELs more conservative compared to the reference solution needs to be considered. Another point is that only the loads at two positions at the offshore wind turbine were considered. Here it should be investigated to what extent the results can also be transferred to other positions on the wind turbine. Furthermore, only the operating wind turbine was investigated. However, especially for offshore wind turbines, idling load cases can also be relevant for the lifetime of the wind turbine. For this reason, the lifetime reassessment should be repeated for an idling offshore wind turbine.

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