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Validated extrapolation of measured damage within an offshore wind farm using instrumented fleet leaders

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Abstract. As the older wind farms are slowly reaching their design lifetime, topics like fatigue and lifetime assessment gain importance. To decide on a possible lifetime extension of the turbine and its foundation, an accurate fatigue assessment for every wind turbine in the farm is needed. As the installation of specific sensors needed for a fatigue assessment is too time consuming and costly, the “Fleet Leader Concept” is applied and validated in this paper. Here, a few turbines are instrumented and a fatigue assessment based on rainflow counting and Miner’s rule can be performed. For a farm-wide fatigue assessment, the obtained damage is extrapolated towards the other turbines. Sample based bootstrapping is performed to introduce an uncertainty on the results. A successful extrapolation was obtained for in-field measurements at an older offshore wind farm. In general, relative errors of less than 5% on damage were found.

1. Introduction

The existing (offshore) wind farms are growing older and thus slowly reaching their design lifetime. [1] expresses concerns about some approaches used in design, for example the p-y method. These approaches may have led to additional conservatism in design and thus a lifetime extension may be possible. In order to support operators in this decision, an accurate fatigue assessment is needed for every wind turbine and foundation in the farm. Currently the available (SCADA) data at an (offshore) wind turbine does not contain enough information nor the right measurements to perform turbine-specific lifetime assessments. Therefore the installation of additional sensors on the turbine’s substructure, such as strain gauges, is necessary [2]. However, installing strain gauges is still considered quite expensive for the operators due to the need for experienced personnel to install, a limited window for installation offshore and the necessary surface preparation. The current practice in industry is to instrument only a few wind turbines (about 10%) in the farm by installing additional sensors on those. If the objective is to assess the lifetime of the entire farm, this requires the extrapolation of the measurements from those turbines to predict the fatigue life of the other wind turbines. The idea of extrapolating measurements from instrumented turbines to non-instrumented turbines was introduced for blade loading by [3] as the “Fleet Leader Concept” and will be applied on turbine foundations



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of an offshore wind farm in this paper. The followed methodology consists in calculating the actual damage accumulated during each 10 minute time interval by applying rain flow counting and Miner's rule on the measured fore-aft bending moment. The accumulated damages are then extrapolated towards other turbines in the farm using environmental conditions only, more in particular wind conditions.

2. Measurement Campaign

2.1. Monitoring setup

The methodology proposed in this contribution will be validated using measurements taken at three offshore turbines of 2MW, located in the same offshore wind farm. These turbines, referenced to as T1, T2 and T3, are installed on a monopile foundation, all three with a similar design. Two of the installed turbines, T1 and T3, are located in the middle of the farm while one, T2, is located at the edge of the farm.

These three turbines were instrumented with strain gauges. A total of six strain gauges were installed on the interface between tower and transition piece. The measured strains are used to calculate the bending moments in fore-aft and side-side direction, using the nacelle orientation of the turbine as available in the SCADA data [4].

2.2. SCADA data

During the measurement campaign, a subset of 10 min SCADA data was available. Among the available parameters are mean yaw angle, mean produced power, mean wind speed and standard deviation of wind speed. The turbulence intensity is calculated by dividing the standard deviation of wind speed by the mean wind speed.

3. Data processing

3.1. Damage calculation

For this contribution, the resulting signal for bending moment at the TP-tower interface was split up into intervals of 10 minutes. For each interval, the accumulated damage was calculated based on the classical approach using rain-flow counting and Miner's rule, as given by Equation 1, where D is the accumulated fatigue damage, n_i the occurred number of cycles and N_i the number of cycles to failure. The latter is given for every stress range by the chosen S-N curve. The stress ranges as measured are multiplied by the combined safety factor (including scale effect, stress concentration factor and material safety factors) as suggested by [5]. The resulting stress ranges are distributed over 500 predefined bins for every 10 minute interval separately. The bin centers of the predefined bins are logarithmically spaced between 10 kPa and 1 GPa.

$$D = \sum_{i=1}^k \frac{n_i}{N_i} \quad (1) \quad \begin{cases} \left| x_i - \frac{x_{i-1} + x_{i-2}}{2} \right| > \max(p \cdot x_i, T) \\ \left| x_i - \frac{x_{i+1} + x_{i+2}}{2} \right| > \max(p \cdot x_i, T) \end{cases} \quad (2)$$

3.2. Data exclusion

Only 10 minute time intervals during which the turbine produced power were considered during the analysis. On top of that, data points for which the required meteorological measurements are not available are excluded from the calculations. Moreover data points with possible unreliable SCADA data are removed. More specifically, all values lower than a predefined minimum value or higher than a predefined maximum value were excluded. The chosen set of criteria is given in Table 1 and reflects improbable or impossible values for SCADA. Moreover to exclude one time outliers, all values x_i for which all expressions in Equations 2, where p is a predefined percentage

and T a predefined threshold value, are fulfilled are excluded too. The values chosen for p and T are given for each parameter in Table 1.

Table 1: Predefined values for different SCADA parameters during filtering

	wind speed (m/s)	TI (%)
absolute minimum	0	2
absolute maximum	50	999
p (%)	100	100
T	5	20

4. Fleet Leader Concept

The applied extrapolation method towards other turbines is proposed in Figure 1. This method consists of two main parts: the damage binning (of the fleet leader) and the damage extrapolation (towards another turbine), respectively elaborated upon in Section 4.1 and Section 4.2. For both stages, some choices have to be made. These choices are indicated in diamonds in Figure 1 and might influence the results significantly. For this paper the choices are made based on experience, explained and well documented during this contribution. The required data for the next step is indicated in circles and the needed actions are indicated in squares. All steps are explained in more detail in the following two sections. This methodology is based on the one presented in [6] for damage extrapolation of offshore wind turbines over time.

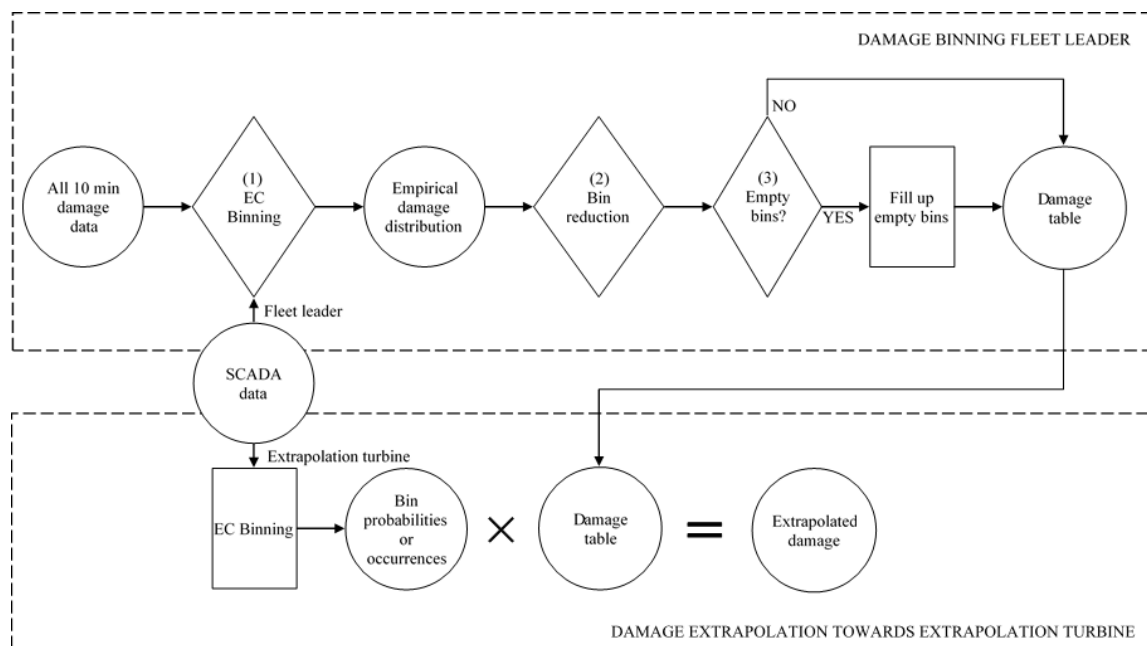


Figure 1: A simplified overview to extrapolate damage data from one turbine to another, with indication of several choices that are part of the procedure.

4.1. Construction of the damage table

To account for the difference in environmental conditions among the different turbines, the measured damage at the fleet leader is linked with specific environmental conditions as occurred

at the fleet leader. Several environmental parameters influence damage accumulation, such as wind speed or turbulence intensity. To link the measured damage to a specific environmental condition, the damage data is binned based on the measurements of the required environmental parameters. Which environmental parameters are of interest is the first choice that has to be made during the process, indicated by (1) in Figure 1. In this paper, two different options are applied and compared. The first only considers the wind speed, the second a combination of wind speed and turbulence intensity. As suggested by [7], a standard bin size of 1m/s for wind speed is taken. Only for wind speeds below 1.5m/s a bin size of 1.5m/s is taken and for wind speeds between 22.5m/s and 26.5m/s the bin size is increased to 2m/s . Moreover the highest bin contains all data points for which the wind speed exceeded 26.5m/s . Given the strong dependence of turbulence intensity to wind speed, it is chosen to define the bin borders for this parameter separately for each wind speed bin. Four different bins are created for each wind speed bin based on the 25th, 50th and 75th percentile. The lowest bin border is chosen well below the minimum value to include all data points. The highest bin border is chosen well above the maximum value for the same reason. The values of 0 and Inf can be chosen respectively.

The final binning of the damage data results in a damage table containing empirical damage distributions for each possible environmental condition. However, to extrapolate damage, only one value for every bin is preferred instead of all damages falling inside the bin. This damage represents the damage the turbine has accumulated while operating in these environmental conditions during a specific time interval, e.g. one year ($D_{\text{yearly},i}$). Here, the appropriate metric has to be chosen to reduce the damage table. An obvious choice might be to take the mean value of damage measurements in one bin, as is done for this contribution. However, any statistical metric can be used to obtain one value, e.g. the 75th or 90th percentile. This choice is represented by (2) in Figure 1. A discussion on the impact of different metrics on the final outcome can be found in Hübler et al. [6]. The obtained damage tables based on wind speed are shown for all turbines in Figure 2. This is done both for operational data only and for parked conditions only. A clear difference in damage accumulation can be observed. For this farm, less damage is accumulated during parked conditions than during operational conditions.

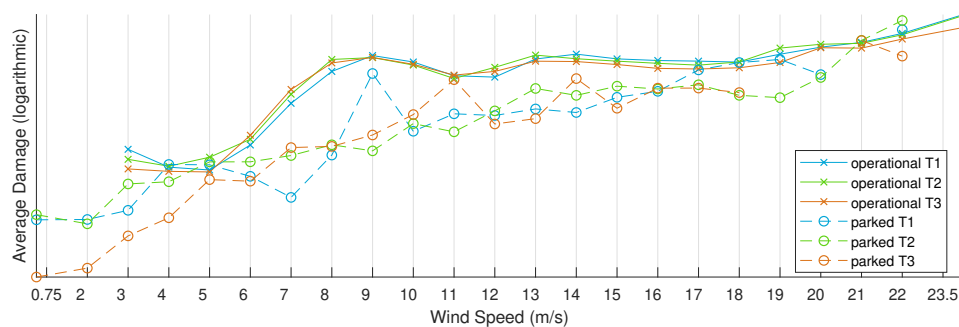


Figure 2: Damage tables, binned based on wind speed, for all three turbines for both operational conditions and for parked conditions.

As already explained, the damage table can be composed based on several (combinations of) environmental parameters. Ideally the environmental parameters and their bin sizes and limits are chosen in such a way each bin contains enough damage data. In reality however it is possible and even very likely some combinations of environmental conditions did not occur during the measurement period. In that case empty bins should be filled with a well considered value. Depending on the availability of the needed information, the filling can be based on design documents or data-driven. This is the third choice to be made, represented by (3) in Figure 1. If design documents contain information about the load case tables obtained by simulations,

those values can be used to fill up the empty bins in the damage table. If this information is not available from design, as was the case for this wind farm, another strategy can be followed. Each empty bin is filled with the maximum value found in the neighboring bins. This is shown in Figure 3, where the two transparent bins initially were empty. In both cases, the neighboring bins are indicated with purple or orange lines and the highest damage of these is copied to the empty bin.

Once the empty bins are filled, a damage table related to environmental conditions is obtained for the fleet leader.

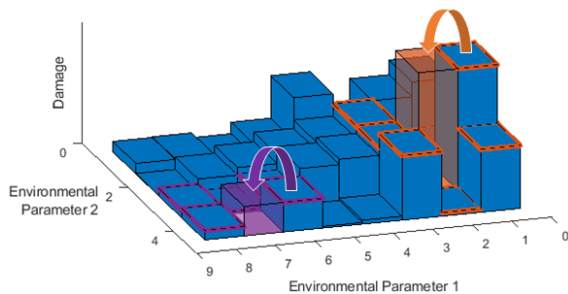


Figure 3: Conceptual illustration on how empty bins were filled. The maximum value found in the surrounding bins of the damage table is used.

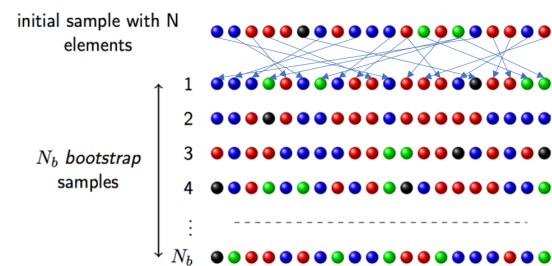


Figure 4: Conceptual illustration of bootstrapping

4.2. Extrapolating damage towards another turbine

The final goal is to estimate the yearly damage at one turbine, using the measured damage at the fleet leader and the specific environmental conditions at the turbine in consideration. These specific environmental conditions are obtained by binning the available SCADA data of the extrapolation turbine in the same way the damage data of the fleet leader was binned. This is shown as a rectangle in Figure 1. This binning results in a number of occurrences for each bin and normalized into bin probabilities for the extrapolated turbine P_r^{ET} . To find the extrapolated yearly damage, the resulting bin probabilities are multiplied by the damage table as calculated for the fleet leader. By summing up the result, the extrapolated yearly damage D_{yearly}^{ET} is obtained. This is summarized by Equation 3. This procedure can be done for every wind turbine in the farm, instrumented or non-instrumented.

$$D_{yearly}^{ET} = \sum_{i \in ECbins} D_{yearly,i}^{FL} \cdot P_{r,i}^{ET}$$

4.3. Reliability of lifetime calculation

In most cases, the amount of available damage data is limited, especially for some rare bins for high wind speeds. As a consequence, the empirical damage distribution in some bins is quite uncertain, and therefore, the reduced damage metrics, here the mean damages, are uncertain as well. That is why for the last part of this analysis, a look is taken at the uncertainty of the extrapolated damage calculation. In statistics, bootstrapping [8] is frequently used to estimate an unknown distribution based on limited known samples. In the context of wind energy, bootstrapping was already applied, for example, in the presence of limited wind data [9]. In the present case, bootstrapping is used to estimate the unknown empirical damage distribution in each bin by only using the available damage values. The general concept of bootstrapping relies

on random sampling with replacement. Here, the damage extrapolation is repeated multiple times to give an estimate of the variation of the estimated damage. For each repetition, not all available measurements $N_{m,i}$ in a bin i are used to calculate the average damage for that bin. Instead $N_{m,i}$ random samples with replacement, i.e. the same measurement can be picked more than once, are drawn. This random combination of measurements is then used to calculate the average damage for that bin. This is illustrated in Figure 4. More information regarding the statistical theory of bootstrapping can be found in Mooney and Duval [10].

In this analysis, this procedure is repeated N_b ($= 10000$) times for every bin, resulting in N_b damage tables and finally in N_b different values for estimated damage. These resulting distributions can then be plotted for each turbine. As such, an uncertainty on the final resulting extrapolated damage is obtained.

5. Results

In theory a total of 52560 datapoints are available for 1 year of data. However not all data was withheld for this analysis (as explained in Section 3.2). Also periods during which no reliable strain measurement is available, e.g. when the monitoring system was not operational, are not considered.

After the initial data checks 72 to 83% of the theoretical maximum of data was used in the evaluation of the fleet leader concept. The majority of rejected data (over 50%) is due to the turbine not producing power.

5.1. Environmental and operational conditions

The first step of the fleet leader analysis is an inspection of the environmental and operational conditions of the different turbines.

Figure 5 shows the difference between the wind speed distribution measured at T1 and T3 with respect to the one measured at T2. To avoid any differences in environmental conditions during the analyzed period due to different removed datapoints, only time instances where all three turbines have proper data are used to calculate the wind distributions.

From the derived difference between wind speed distributions, it is worth pointing out that the distribution observed at T2 is skewed to lower wind speeds, compared to T1 and T3. It is possible that this deviation towards lower wind speeds is due to a sensor misalignment at T2, leading to an underestimation of the wind speeds.

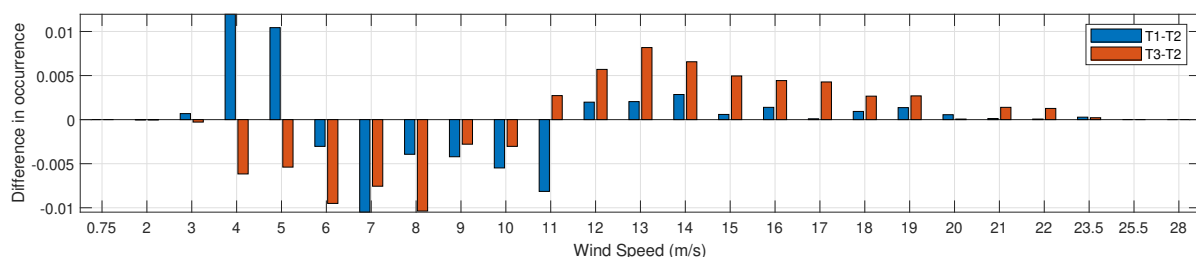


Figure 5: The difference between the as measured (SCADA) wind speed distributions at T1 and T3 compared to the wind speed distribution at T2. The distributions were calculated based on a reduced filtered dataset where data corresponding to a filtered timestamp of any turbine was removed for all turbines.

T2 operated more often in lower turbulence intensities than T1 and T3, as can be seen in Figure 6. This can be explained by its location in the farm, being at the edge and thus receiving non-turbulent wind for some wind directions.

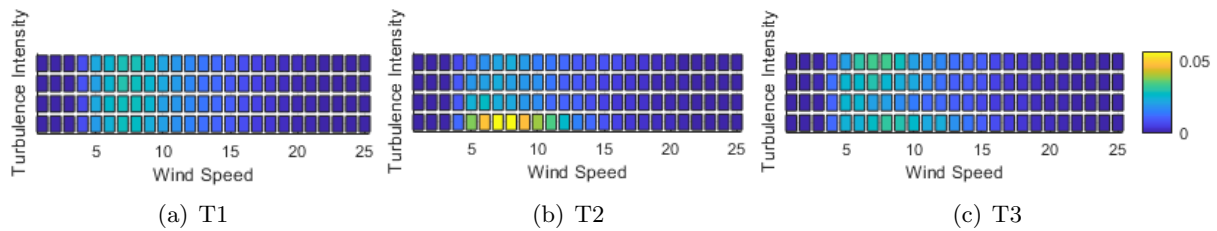


Figure 6: Environmental distributions based on wind speed and turbulence intensity, where the colors represent the probability of the bins: a blue bin has low probability, while a yellow bin has a high probability.

5.2. Fleet leader validation

To validate the concept of a fleet leader extrapolation each of the three instrumented turbines is used as a fleet leader, with results extrapolated to all instrumented turbines. Therefore, 9 possible combinations were obtained (shown in Figure 7). Each combination has its own representation using $ET(FL)$, where ET indicates the extrapolation turbine and FL the fleet leader. These representations are also shown in Figure 7.

A good result is when the prediction from the fleet leader model matches with actual damages measured from the monitoring system, at the TP-TW interface of the turbine.

In Figure 7 the resulting extrapolated yearly damages are shown relative to the actual yearly damage. For the calculation of yearly damage, the assumption is made that the environmental conditions are the same during the time data lacked or was filtered out, as during the time proper data was recorded.

Each extrapolation is done twice. First using one environmental parameter, being wind speed. The resulting distribution is shown in blue, where the blue line indicates the mean value of the distribution. Secondly using two environmental parameters, being wind speed and turbulence intensity. These results are shown in purple.

The actual damage measured by the monitoring system at the extrapolation turbine is shown by the green line in Figure 7, while the damage measured at the fleet leader is shown by the yellow line. The closer the resulting extrapolation is to the green line (actual damage), the better the result.

In general, the extrapolation based on wind speed (blue distributions and lines) only shows extrapolated damages close to the actual measured yearly damages, with differences between the mean value of the extrapolated damage distribution and the actual damage below 3%.

Looking closer to the results, one can observe a high similarity in measured yearly damage of T2 and T3 in T2(T3) and T3(T2) since the green and yellow line are very close to each other. Based on the small difference between these measured damages, one might assume no extrapolation based on SCADA data is necessary. However, this high similarity seems rather coincidental. On the other hand, the extrapolated damage distributions based on wind speed only also approximate the actual value very good. The added value of the fleet leader concept is shown by the combination of T1 and T3, T1(T3) and T3(T1). Here, an improvement in prediction is clearly visible by including environmental conditions.

The results based on the combination of wind speed and turbulence intensity, don't show any added value in this case. Results for T1(T3) and T3(T1) are comparable to those obtained using wind speed only. This is probably because both turbines are standing in the middle of the farm and thus seeing increased turbulence intensity levels for all wind directions. It is believed an improvement would be obtained if a turbine at the edge of the farm is included.

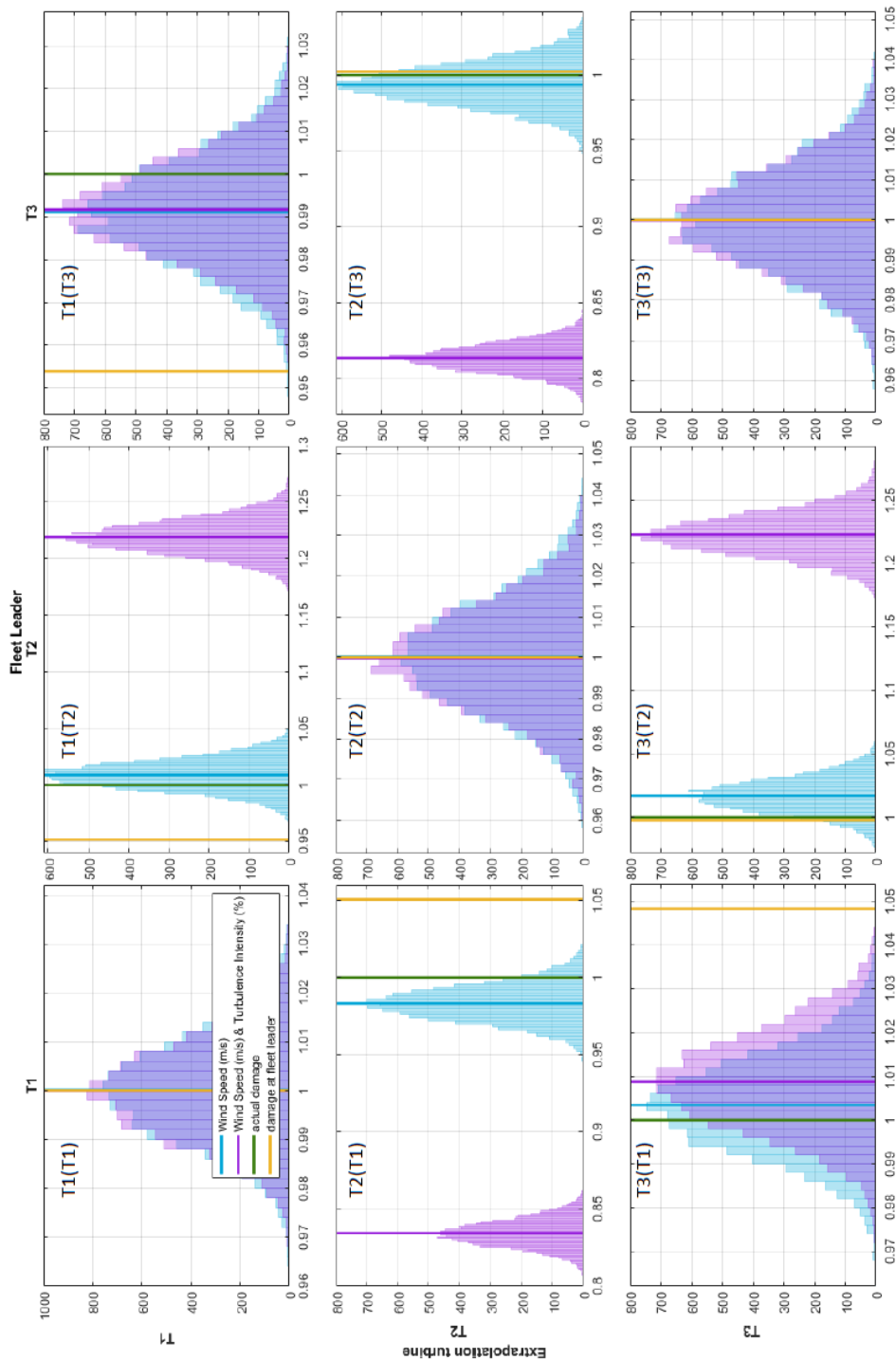


Figure 7: Extrapolated yearly damage for each combination of fleet leader and extrapolation turbine, normalized to the expected, measured damage at the extrapolation turbine. The damage is extrapolated based on wind speed only (blue) and a combination of wind speed and turbulence intensity (purple). For each resulting damage distribution, the mean value is shown by a line in the same color. In each figure, the damage measured at the extrapolated turbine is shown in green. The closer the extrapolated damage distribution are to the green line, the better the result. The measured damage at the fleet leader is also shown, in yellow. Each combination has its own representation using $ET(FL)$, also shown in the figure.

However, all results when T2 (at the edge of the farm) is involved as fleet leader or extrapolation turbine are much worse with differences over 20% between actual damage and the average extrapolated damage. When T2 is taken as a fleet leader, the extrapolated damage for T1, T1(T2), and T3, T3(T2) is overestimated. This indicates the damage seen by T2 is higher than the damage seen by the other two turbines for the same environmental conditions. This can also be seen for wind speeds up to 13 m/s, for example in Figure 8. The reason for this difference in damage can be physical but can also be related to the erroneous wind speed measurement referred to earlier. Therefore the measured damages at T2 might be allocated to environmental conditions with an underestimated wind speed, which do not coincide with the actual environmental conditions with a higher wind speed. This might lead to seemingly higher damages for the same environmental conditions.

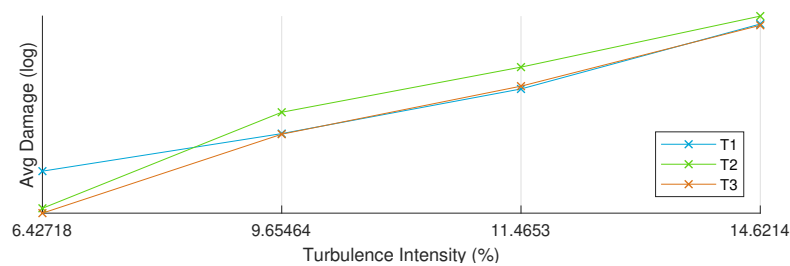


Figure 8: Damage tables, binned based on wind speed and turbulence intensity, for all three turbines for wind speeds around 10 m/s.

Although results based on wind speed only suggest no such difference, the effect of higher damages allocated to too low wind speeds is counteracted by the lower turbulence intensities measured at T2. A clear variation in fatigue damage can be seen when T2 is in and outside the wake, Figure 9, leading to actual lower damage for the same wind speed for wind directions between 30° and 210° .

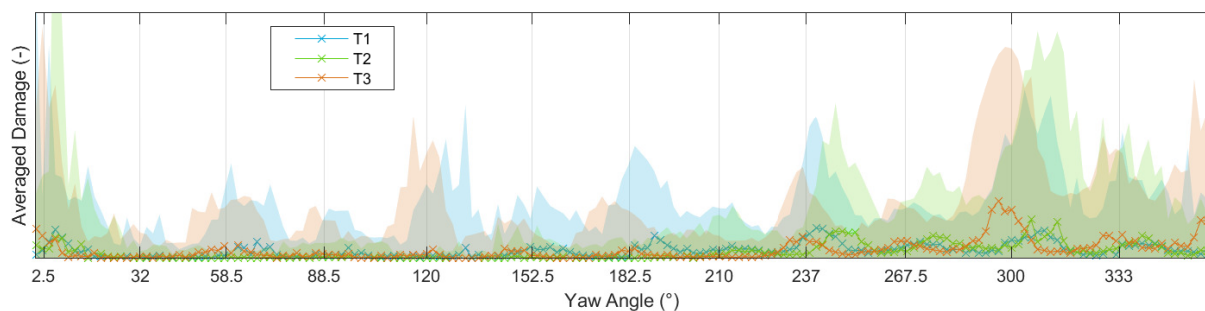


Figure 9: The average fatigue damage varies with the yaw angle, as shown for all three turbines. For wind directions where T2 is out of wake, i.e. from 30° and 210° , we can see decreased damage.

6. Conclusion and way forward

The presented methodology can be used to estimate the accumulated damage at all turbines within the farm, using 10 minute SCADA data of all turbines and strain measurements at TP-TW interface at a limited number of turbines (fleet leaders). Moreover, accumulated damage during missing periods of strain measurements at the fleet leaders can be estimated as well. It is important to note that for this application, the filter regarding the available and reliable strain measurements is only needed for the fleet leaders, not for the extrapolation turbines.

As mentioned in Section 3.2, only data during normal operation was considered. However, for a realistic indication of actual accumulated damage, all operational conditions should be accounted for. As damage is accumulated differently during normal operation compared to parked conditions, the proposed methodology would be applied separately on operational data and on data during parked conditions.

The number of rotor stops for each turbine individually should be taken into account as well. Rotor stops can be detected based on log documents or based on the measured strain signals. As shown in Figure 10, high stress cycles are obtained leading to increased damage. Again, to extrapolate the damage caused by rotor stops, the proposed methodology should be repeated for rotor stops separately.

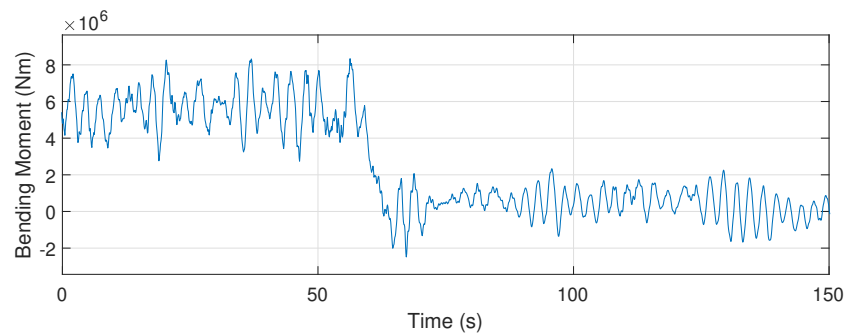


Figure 10: Measured bending moment during a rotor stop

The results from the fleet leader can be translated into an indication for lifetime of the entire wind farm, but then additional information is needed. This additional information includes the SCADA data of each turbine and the expected environmental conditions over the entire lifetime of the wind turbines, e.g. as used in design. Moreover, the use of the as-designed stress concentration factors, safety factors, size effects and S-N curves is advisable.

Finally, it should be noted the obtained results in this paper were based on measured interface loads between tower and transition piece. Additional analyses and research is still needed to know how these resulting damages can be translated towards other locations within the substructure of the wind turbine.

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