

Fatigue reassessment for lifetime extension of offshore wind monopile substructures

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Abstract. Fatigue reassessment is required to decide about lifetime extension of aging offshore wind farms. This paper presents a methodology to identify important parameters to monitor during the operational phase of offshore wind turbines. An elementary effects method is applied to analyze the global sensitivity of residual fatigue lifetimes to environmental, structural and operational parameters. Therefore, renewed lifetime simulations are performed for a case study which consists of a 5 MW turbine with monopile substructure in 20 m water depth. Results show that corrosion, turbine availability, and turbulence intensity are the most influential parameters. This can vary strongly for other settings (water depth, turbine size, etc.) making case-specific assessments necessary.

Keywords: lifetime extension; fatigue reassessment; offshore wind turbine; elementary effects; monitoring.

1. Introduction

Offshore wind is still a young industry where most wind farms have less than 10 years of operational experience [1]. However, in the soon future, the first larger offshore wind farms will reach a mature age (e.g. Anholt, London Array). It then becomes increasingly important to reassess the structural integrity of the wind turbine support structures in order to optimize the operation for exploitation of structural reserves and to decide on lifetime extension. Optimization of maintenance and inspection routines is equally important throughout the entire lifetime. Already today, an important question for the offshore wind industry is: how to determine the turbine-specific fatigue damage accumulated throughout the operational life in order to decide about lifetime extension?

The design lifetime of offshore wind parks is typically 20-25 years. Extension of the service time offers an increase in profit of existing projects. The decision about lifetime extension is driven by the remaining useful lifetime of all wind turbine components. Uncertainties in environmental conditions, design models and operational loading make it difficult to accurately predict the remaining useful lifetime. In the design phase, these uncertainties are covered through the use of a partial safety factor method and conservative assumptions in input parameters [2]. Local conditions often differ from design assumptions since there is a cost optimum between design accuracy and design effort. Information from monitoring and inspection throughout the service phase of offshore wind farms can be used in structural reassessment to improve assumptions on input parameters and recalculate fatigue and extreme loading. Consequently, conservatism in the design models can be reduced. This leads to a more realistic (and possibly larger) calculated lifetime.



Up to now, there is only little experience available in lifetime extension of wind turbines. The first standard on lifetime extension of wind turbines was recently published by DNV GL [3]. It is applicable to on- and offshore likewise. The standard suggests a twofold assessment approach: (I) renewed lifetime calculation in combination with (II) assessment through inspection. Renewed lifetime calculation can either be “simple”, “detailed”, or “probabilistic” [3]. It refers to a rerun of numerical wind turbine simulation models taking into account local conditions and current state of the art. In addition, there are only few academic publications addressing lifetime extension of OWTs. Ziegler and Muskulus [4] suggest a three-step assessment approach for lifetime extension of offshore wind monopiles consisting of structural reassessment, prediction of remaining useful lifetime, and a decision model. The output of structural reassessment is the current amount of damage of the OWT substructure [4]. This information is then used to predict the remaining useful lifetime taking into account uncertainties in future environmental and operational conditions. The decision model employs decision criteria on the calculated remaining useful lifetime and associated operational incomes and costs. Ziegler and Muskulus [4] conclude that inspections for fatigue cracks are important to rule out gross errors but numerical fatigue reassessment and monitoring are needed for prediction of remaining useful lifetimes. An analysis of end of life scenarios and failure modes is presented in [5]. Kallehave et al [6] show that an under-prediction of the first natural frequency in design of 10% leads to an increase in fatigue lifetime of 88% for a monopile design governed by hydrodynamic loading. Ziegler et al [7] showed that fatigue loads are sensitive to site conditions and can vary significantly position-specific in large offshore wind farms. In a wind farm with 150 monopile-based OWTs in 30-40m water depth, fatigue loads were shown to differ up to 25% [8]. These studies indicate that there is a potential for numerical fatigue reassessment, however no overall analysis establishing the link to lifetime extension is available yet.

This paper analyses the suitability of numerical fatigue reassessment for monopile substructures of OWTs. In a case study, residual fatigue lifetimes are calculated for expected variations (upper and lower bound) of environmental, structural and operational conditions. Conclusions on important parameters to monitor are drawn from a global sensitivity analysis. Sensitivity measures are calculated with the elementary effects method in order to reduce the sample space for the computational expensive simulation [9]. The remainder of this paper is organized as follows. Section 2 presents the approach to numerical fatigue reassessment. Two methodologies of sensitivity analysis are shown in Section 3. Results are discussed in Section 4 and concluded in Section 5.

2. Methodology for fatigue reassessment

In numerical fatigue reassessment (also referred to as renewed lifetime simulation) structural loads are recalculated through an update of the original design model and assumptions in accordance with current versions of design standards. For onshore wind turbines, it is current practice to use primarily the following two arguments to prove the existence of remaining useful lifetime for extension of wind farm operation [10]:

1. wind turbines operate on a site with less wind resources than the design wind class, and
2. production time of wind turbines is lower than in design (availability <100%).

For OWTs the first argument is not suitable as support structure designs are done site-specific according to IEC 61400-3 [11]. Additionally, reduced turbine availability might not be a valid reason for lifetime extension offshore since turbine idling can increase fatigue loading due to a lack of aerodynamic damping [12]. Consequently, fatigue reassessment of OWTs has to focus on different criteria. The significance of various criteria for OWT lifetime extension is demonstrated in a case study using a global sensitivity analysis.

2.1. Case study: numerical model and load simulation

The generic OWT assembly defined in Phase I of the OC3 project was used for the case study. This assembly consists of the NREL 5 MW reference wind turbine supported by a monopile in 20 m water

Table 1. Design basis with load cases and corresponding frequency of occurrence [15]. V_W : mean wind speed, TI : turbulence intensity, H_S : significant wave height, T_P : wave peak period, occur: frequency of occurrence.

V_W [m/s]	TI [-]	H_S [m]	T_P [s]	occur [-]
2	29.2	1.07	6.03	0.062
4	20.4	1.1	5.88	0.111
6	17.5	1.18	5.76	0.141
8	16	1.31	5.67	0.15
10	15.2	1.48	5.74	0.141
12	14.6	1.7	5.88	0.12
14	14.2	1.91	6.07	0.094
16	13.9	2.19	6.37	0.068
18	13.6	2.47	6.71	0.045
20	13.4	2.76	6.99	0.028
22	13.3	3.09	7.4	0.017
24	13.1	3.42	7.8	0.009
26	12	3.76	8.14	0.005
28	11.9	4.17	8.49	0.002
30	11.8	4.46	8.86	0.001

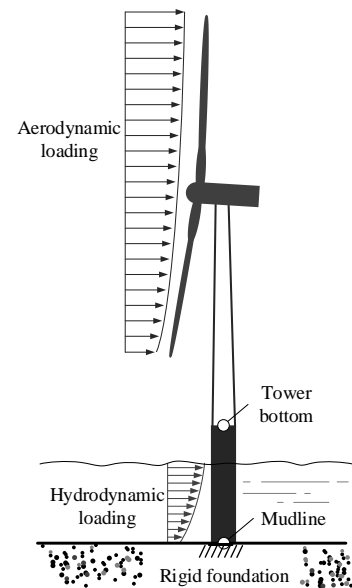


Figure 1. Model of offshore wind turbine used in numerical analysis.

depth [13]. Figure 1 shows the numerical model of the OWT assembly used in this case study. All dimensions were implemented in a finite-element model in FAST (Version 8, NREL) according to the original OC3 specifications. FAST is an aero-hydro-elastic software for simulation of integrated dynamic responses of wind turbines in the time-domain [14]. Coupled dynamic response of the OWT to aerodynamic and hydrodynamic loading is analysed for nodes at tower bottom and at mudline.

Time-domain simulations were performed for the OWT being in power production and in idling in accordance with the IEC standard [11]. Design assumptions and environmental conditions are adapted from the Upwind Design Basis (K13 Shallow Water Site) [15]. The lumped environmental conditions are stated in Table 1. The wind speeds between 4-24 m/s correspond to power production and the remaining ones to idling. The lumped conditions were obtained from full scatter diagrams of correlated wind and wave conditions. The lumping was done so that the reduced number of conditions presented in Table 1 cause the same amount of fatigue damage as all conditions from a full scatter diagram [15]. Variation in short-term wind speed was modelled with a Kaimal turbulence spectrum. The stochastic wind field over the rotor area was generated with the simulation program TurbSim (Version 1.06.00; NREL). A JONSWAP wave spectrum with a peak enhancement factor of 3.3 was used in FAST to generate wave time series. Currents and yaw-misalignment were neglected in the simulation. The structural analysis was done assuming unidirectional wind and wave conditions.

One hour simulations were performed for each lumped state. Rainflow counting on the stress time series yielded the stress ranges and the corresponding number of cycles for the lifetime of the structure. Damage for circumferential butt welds at TB and ML was calculated with Miner's rule of linear damage accumulation [16]. The material resistance against cyclic loading is taken from the SN-curves with detailed category "D" with cathodic corrosion protection [17]. The failure criterion was taken as damage equalling 1. The lifetime of the structure was calculated by linearly extrapolation of the damage value obtained for 20 years operation.

2.2. Parameters in fatigue reassessment

The amount of deviation of parameters between design and reality is highly project-specific and depends on the quality of initial site assessment used in design. Sources of uncertainty are

- *aleatoric uncertainties* in random processes, e.g. wind, sea state, fatigue crack growth, and
- *epistemic uncertainties* including data, statistical and model uncertainty.

Table 2. Design basis and upper and lower bound of expected variability of primary environmental, structural and operational conditions. X: generic 5% variation.

Category	Parameter	Unit	Lower bound	Design	Upper bound	Source
Environmental	Mean wind speed v_w	[m/s]	9.6	10	10.4	[18,19]
	Turbulence intensity TI	[-]	$0.95 f(v_w)$	$f(v_w)$	$1.05 f(v_w)$	[15], X
	Significant wave height H_S	[m]	$0.95 f(v_w)$	$f(v_w)$	$1.05 f(v_w)$	[15], X
	Wave peak period T_p	[s]	$0.95 f(H_S)$	$f(H_S)$	$1.05 f(H_S)$	[15], X
Structural	First natural frequency f_{nat}	[Hz]	0.271	0.276	0.304	[6]
	Damping ratio ζ	[%]	0.196	0.2	0.204	[20]
	Free corrosion	[year]	10	0	0	[21]
Operational	Turbine availability	[%]	80	100	100	[22]

A central issue is the lack of published data regarding parameter deviations and their distributions in reality compared to design assumptions. The parameters considered in this case study are defined based on data and expert opinion (cf. Table 2). If no information is available, a generic variation of 5% around the design assumption was chosen.

The change in annual mean wind speed is obtained by varying the scale parameter of the Weibull distribution of wind speeds. The Weibull distributions corresponding to the upper and lower bound are shown in Figure 2 (left) and Table 3. Turbulence intensities, significant wave heights, and wave peak period are linearly scaled as a function of the wind speeds given in Table 1.

The first natural frequency of the monopile support structure represents, for example, variations in soil conditions and scour. It is adapted by scaling of the monopile and tower stiffness. This also changes the quasi-static response of the structure, but such changes do not significantly influence the fatigue damage. References state mainly an over-prediction of the first natural frequency in design due to conservatism in soil parameters [6]. This is reflected in this study by choosing a larger deviation of the upper bound and only minor change of the design value to the lower bound. The damping ratio is adjusted by a scaling of structural damping. Internal corrosion (corrosion from inside the monopile) is neglected in many designs. However, corrosion measurements have shown that internal corrosion can be larger than expected [21]. In addition, external corrosion protection may be consumed faster than anticipated in design [21]. Consequently, the lower bound of corrosion is defined as the time the monopile spent in free corrosion, while the upper bound is identical to the design value (no free corrosion). The SN-curve for seawater without corrosion protection is applied for the time in free corrosion [17]. The damage calculated from the protected and free corrosion SN-curves is linearly weighted. Both SN-curves are shown in Figure 2 (right).

OWTs have designed for 100% availability in the past; however experience has shown that unscheduled maintenance and repairs can severely increase turbine downtime [22]. The lower bound of availability is taken as 80% which is the mean availability reported in [22] for five UK wind farms in their early lifetime. The turbine is assumed to idle when it is not available. Additional idling time is due to wind speed being outside the operational range. Secondary parameters, such as soil conditions, scour, and marine growth, are not mentioned in Table 2, since their influence on fatigue life is assumed to be represented through the change of natural frequency and damping.

Table 3. Weibull scale and shape parameter and corresponding annual mean wind speed (MWS).

	Scale parameter [-]	Shape parameter [-]	MWS [m/s]
Lower bound	10.85	1.97	9.6
Design	11.31	1.97	10
Upper bound	11.78	1.97	10.4

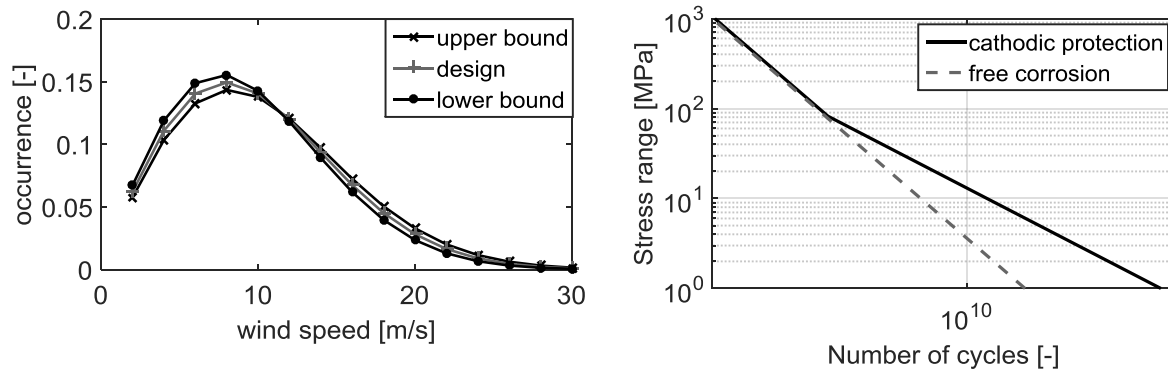


Figure 2. Left: Weibull distribution of wind speeds. The curves are shown for the design value and upper and lower bounds of the Weibull scale parameter. Right: SN-curve for cathodic protection and free corrosion [17].

3. Global sensitivity analysis

Fatigue analysis is computationally expensive due to time-domain load simulation. The simulation time of FAST on a single, standard processor is approximately $0.8 \cdot$ real time. Additionally, the high number of parameters influencing the fatigue lifetime makes global sensitivity analysis with a large sample space unsuitable due to time constraints. For an example, a design basis with 15 loading situations and 8 parameters with only 10 sampling points each requires already $15 \cdot 10^8$ simulations to explore the complete sampling space. This creates the need for alternative approaches to global sensitivity analysis. In this paper, the sampling points of each parameter are reduced to the upper and lower bounds of expected variability. Two types of sensitivity analyses are conducted:

1. One parameter is varied while keeping all other parameters at their design value. This method reveals the importance of a single parameter but cannot provide information on the influence of parameters interacting with each other.
2. Global sensitivity analysis with elementary effects method where selected sampling paths are created [9]. The method reduces the sampling space while still all parameters are varied simultaneously. This enables to capture parameter interaction although simulations are computational expensive.

The sensitivity analysis reveals which parameters have a strong influence on the fatigue lifetime and should be monitored, while less important parameters can be taken at their design value.

Elementary effects is a screening method to detect important parameters in a model [9]. The elementary effect EE_i of the i -th parameter X_i is defined by Morris [23] as the change in model output by variation of the parameter X_i with a specified Δ (cf. Equation 1, adapted from [9]). k is the number of parameters in the model.

$$EE_i = \frac{Y(X_1, X_2, \dots, X_i + \Delta, \dots, X_k) - Y(X_1, X_2, \dots, X_k)}{\Delta} \quad (1)$$

Elementary effects are calculated from random sampling paths which have the following set up:

1. Random initiation of all parameters in all their sampling levels. *Two levels are used in this study for corrosion and availability; all other parameters have three levels.*
2. Each path consists of k steps. In each step only one parameter is randomly lifted up or lowered one level by the amount Δ . Each parameter is selected exactly once. No parameter can be lifted outside the specified range. *In this study there are 8 parameters corresponding to 8 steps in each path. Δ is 1 for corrosion and availability and 0.5 for the other parameters.*
3. n random sampling paths are created. Consequently, n elementary effects EE_{ij} ($j=1-n$) for each parameter exist. *13 paths are used in the case study.*

One exemplary sample path is shown in Table 4.

Table 4. Exemplary sample path for elementary effects method. Grey boxes indicate the parameter change in step *i*. 1=lower bound, 2=design, 3=upper bound. No level 3 exists for corrosion and availability.

	V_w	TI	H_S	T_P	f_{nat}	ζ	corrosion	availability
Initial	3	1	3	2	3	1	1	2
Step 1	3	1	3	1	3	1	1	2
Step 2	3	1	3	1	3	1	2	2
Step 3	3	1	2	1	3	1	2	2
Step 4	2	1	2	1	3	1	2	2
Step 5	2	1	2	1	2	1	2	2
Step 6	2	2	2	1	2	1	2	2
Step 7	2	2	2	1	2	1	2	1
Step 8	2	2	2	1	2	2	2	1

Sensitivity measures are the mean of the absolute of the elementary effects (13 per parameter in this study) and their standard deviation. A large mean value indicates a strong influence of the parameter on the model output [9]. The interactive effect of a parameter with others is captured in the standard deviation of the elementary effects.

4. Results and discussion

4.1. One-parameter sensitivity results

The calculated damage value for 20 years of operation for the investigated welds is 36.09% for tower bottom and 23.3% for mudline. Damage results for the single parameter variation are shown in Table 5. Parameters influencing the lifetime positively (and negatively, respectively) are grouped into hypothetical best- and worst-case scenarios. Analysis of the two scenarios yields the bandwidth of residual fatigue lifetimes. The worst and best case lifetimes are 6.2 years – 71.7 years for tower bottom and 8.4 years – 157.9 years for mudline. The worst case effect on damage is more pronounced than for the best case (cf. Table 5).

Figure 3 presents the one parameter sensitivity results for the extrapolated lifetimes. The results for tower bottom (left) and mudline (right) show the same trends. However, the wave load influencing parameters are more pronounced at mudline (H_S , T_P) while wind influencing parameters have a stronger influence at tower bottom (V_w , TI). This indicates that the importance of parameters is coupled to the governance of aero- or hydrodynamic loading.

For this case study, availability, turbulence intensity and free corrosion have a strong influence on the results. The effect of damping on the fatigue lifetime is negligible at both locations; however the parameter was also only varied by 2%. Free corrosion introduces a severe negative influence and

Table 5. Damage results for tower bottom (TB) and mudline (ML) for one-parameter sensitivity study.

Parameter	Lower bound	Design	Upper bound	Damage at TB [%]		Damage at ML [%]	
				lower b.	upper b.	lower b.	upper b.
v_w [m/s]	9.6	10	10.4	33.8	38.2	21.6	24.8
TI [-]	0.95 $f(v_w)$	$f(v_w)$	1.05 $f(v_w)$	32.9	50.4	21.2	29.7
H_S [m]	0.95 $f(v_w)$	$f(v_w)$	1.05 $f(v_w)$	35.6	36.4	21.9	24.5
T_P [s]	0.95 $f(H_S)$	$f(H_S)$	1.05 $f(H_S)$	36.7	35.5	24.1	22.3
f_{nat} [Hz]	0.271	0.276	0.304	36.3	35.4	23.3	22.3
ζ [%]	0.196	0.2	0.204	36.0	36.0	23.3	23.2
Cr [year]	10	0	0	36.1	97.6	23.3	63.4
Av [%]	80	100	100	29.2	36.1	18.8	23.3
Best case	all variables in fatigue reducing bound			27.9		12.7	
Worst case	all variables in fatigue increasing bound			322.5		239.8	

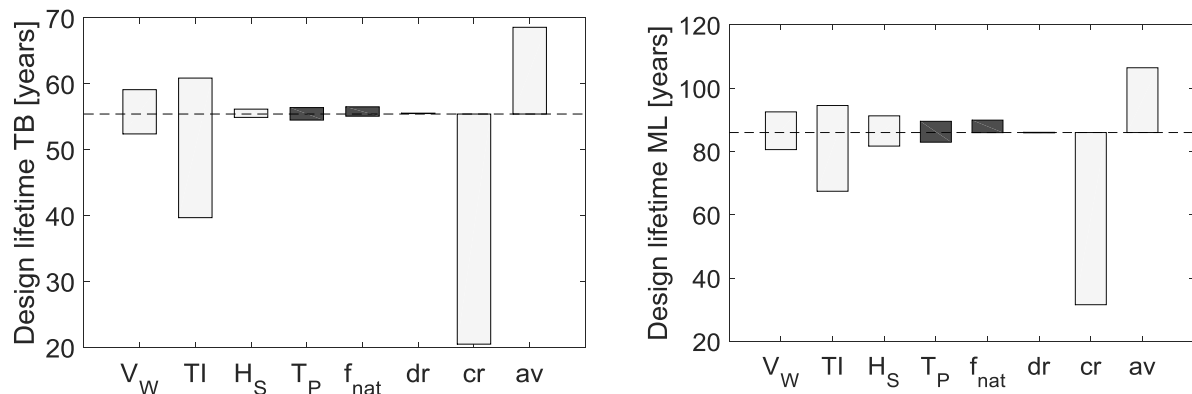


Figure 3. One-parameter sensitivity results for tower bottom (left) and mudline (right). Dark coloured bars indicate an increase in parameter causing an increase in lifetime (upper bound = larger lifetime, lower bound = lower lifetime). Vice versa, for grey coloured bars an increase in parameter causes a decrease in lifetime. Dr: damping ratio, cr: corrosion, av: availability.

should be considered carefully. Reduced availability, wind speed and turbulence intensity offer a potential for lifetime extension in this case study. The linear extrapolation assumes that all conditions stay constant in future operation. If a parameter changes in the life extension period, e.g. an increase in availability due to optimization of operation and maintenance, the fatigue reassessment would have to be adapted.

The worst and best case scenarios lie further out than the linear summation of the effects of each individual parameter. This indicates that parameters affect each other, e.g. a decrease in natural frequency and decrease in wave peak period causes the wave peak frequency to come closer to the first natural frequency leading to higher dynamic amplification.

Figure 4 presents the damage (left) and fatigue lifetime (right) as a continuous function of corrosion and availability for tower bottom. The parameter value of 100% corresponds to the design value – full corrosion protection and full availability. A decrease in corrosion protection leads to more corrosion and consequently reduction in lifetime. The effect of availability is reinforced in the fatigue lifetime plot (cf. Figure 4 right) since the damage reduction is assumed to continue in future years. Idling loads are very low for this case study, so that an availability reduction of 50%, for example, corresponds to also 50 % less damage.

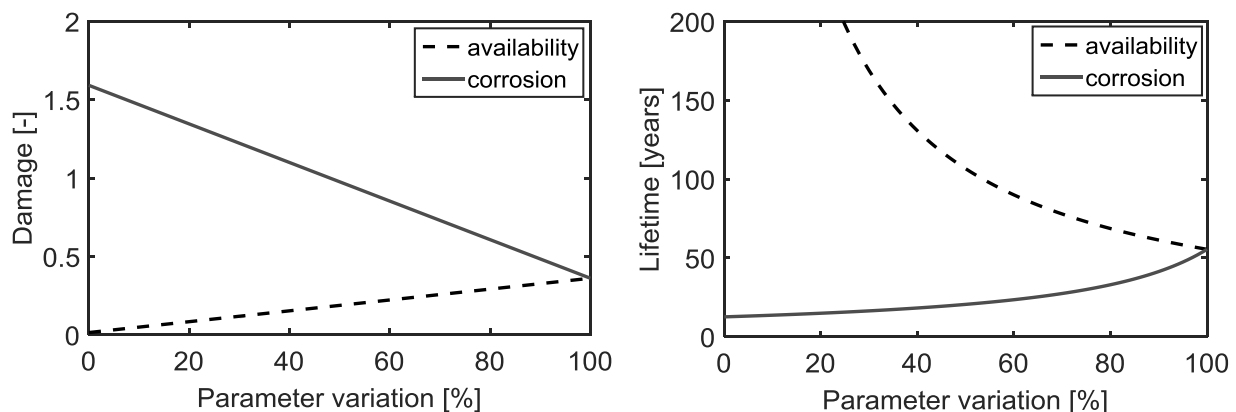


Figure 4. Damage (left) and fatigue lifetime (right) as a function of availability and corrosion for tower bottom. The 100% correspond to both parameters being at their design value.

4.2. Elementary effects results

Results of the sensitivity analysis using elementary effects methods indicate qualitatively the importance of parameters on fatigue reassessment for this case study. In this paper, results are presented for tower bottom exemplarily, but the method can be equally applied to other locations of interest. Figure 5 left shows the lifetime development of the example sample path presented in Table 4. The most significant changes evolve from corrosion (step 2), turbulence intensity (step 6), and availability (step 8) as expected from the single parameter sensitivity analysis. Nevertheless, the increase in wave peak period (step 1) caused also a significant decrease in lifetime which originates through the corrosive setting and upper bound wave heights.

Figure 5 right presents the sensitivity measures of the elementary effects. In line with the results of the single parameter analysis, the parameters turbulence intensity, corrosion, and availability are most influential on the fatigue reassessment. Wave peak period and first natural frequency of the support structure, however, become more important than mean wind speed which is in contrast to the results of the previous section. Additionally, corrosion has a high interaction with the other parameters which can be the reason for a larger influence of hydrodynamic loads. Interestingly, turbine availability has a low interaction with other parameters. This is due to idling loads being very low for this case study compared to loads in turbine operation.

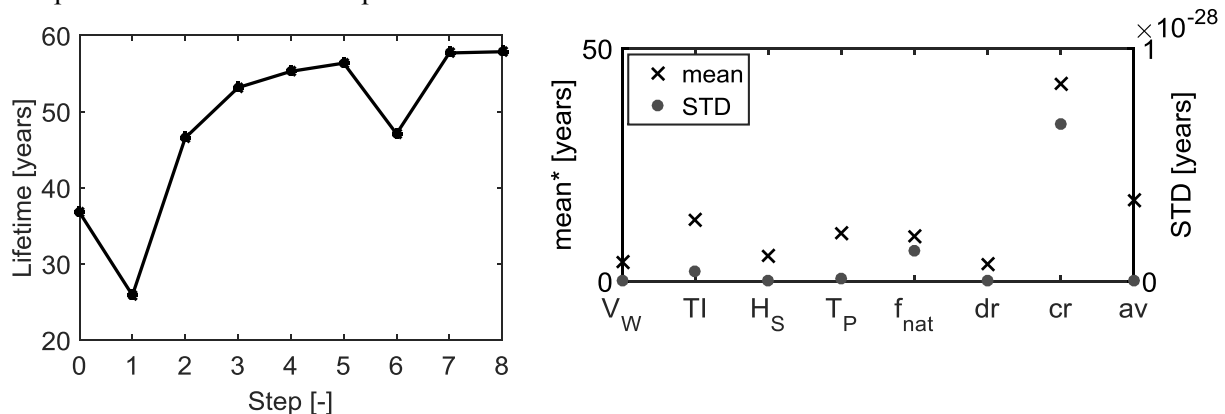


Figure 5. Left: Lifetime development along one sample path at tower bottom. Right: Mean and STD of elementary effects at tower bottom.

4.3. Discussion

The sensitivity results indicate which parameters are important for fatigue lifetimes and consequently should be taken into account in the lifetime extension decision. This provides a basis to decide on the necessity of additional measurements and monitoring. The elementary effects method offered more insight on the importance of variables than standard single-parameter variations while the computational effort is kept small. Therefore, the method is strongly recommended for further use in academia and industry.

The sensitivity of fatigue lifetimes changed for different structural hot spots. The lifetime extension analysis should therefore be tailored to the lifetime critical hot spots. On the other hand, selected parameters, such as corrosion and availability, have an overall strong influence and should be monitored carefully. In addition, structural monitoring concepts can be employed for structural reassessment. Short term monitoring campaigns used for load validation can lead to better estimates of remaining useful lifetimes.

The results cannot be interpreted in the same way as local sensitivity measures since the parameters are not varied in the same range but with the expected difference between their design and reality based on (partly) a subjective expert judgement. In this case study, the analysis applied only a reduced design basis compared to industry practices. Sensitivity results are case-specific and can vary strongly for other settings, e.g. different turbine size and water depth. Especially turbine downtime can yield to an opposite damage development as shown here if the first natural frequency of the structure is closer

to wave peak frequencies (often the case for XL monopiles in deeper water). This makes the fatigue design typically driven by hydrodynamic loading. The lag of aerodynamic damping during idling then worsens fatigue loading dramatically – consequently, low availability increases damage and reduces the fatigue lifetime as presented by Gengenbach et al [24]. Therefore, care should be taken for generalization of results.

5. Conclusion and outlook

Results showed that numerical fatigue reassessment is suitable to identify potential residual fatigue lifetimes of monopile support structures. In industry practise, renewed lifetime calculations are often limited by the non-availability of wind turbine models. In contrast to onshore wind procedures, general trends of the influence of specific parameters on fatigue lifetimes can hardly be derived – case-specific assessments are required.

A global sensitivity analysis using the elementary effects method proved to be suitable to identify important parameters to monitor during the service phase of offshore wind parks. Optimized monitoring concepts can then be employed to reduce parameter uncertainty, design conservatism and potentially prolong calculated fatigue lifetimes. Some of the important parameters are readily available through existing SCADA data (e.g. availability, wind speed), while it's harder to obtain information on other parameters, such as turbulence intensity or damping.

Future research should analyse how fatigue reassessments on a limited number of OWTs can be extrapolated for the entire wind farm.

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