Proc. of the European Safety and Reliability Conference (ESREL 2026)
Edited by José C. Matos, Paulo B. Lourenço, Michael Beer, Daniel Oliveira,
Edoardo Patelli, Hélder S. Sousa, Rui A. Silva and Monica Santamaria

doi: 10.3850/ESREL2026061419_esrel26-p26548-cd

Lifetime load sensitivity analysis of offshore wind turbine

Aidan Napier
EEE, University of Strathclyde, UK. E-mail: aidan.napier.2021@uni.strath.ac.uk

Abbas Mehrad Kazemi Amiri
EEE, University of Strathclyde, UK. E-mail: abbas.kazemi-amiri@strath.ac.uk

Edoardo Patelli
CEE, University of Strathclyde, UK. E-mail: edoardo.patelli@strath.ac.uk

David Malcolm
SSE, Offshore Mechanical Engineering. E-mail: david.malcolm2@sse.com

In the design of offshore wind turbines (OWT), industrial practice simplifies the environmental design conditions in accordance with the standard guidelines, which are based on a limited set of Design Load Case's (DLC). This deterministic design strategy requires the use of partial safety factors (PSF) to account for uncertainty in the design process – since full probabilistic analysis is computationally expensive – which builds in conservatism. During operation, lighter lifetime loads due to uncertainties such as those in the information on the site-specific conditions and milder utilization pre-construction design stage, highlight an opportunity to evaluate and quantify the reserve life introduced in the conservative design practices. This study proposed a computational strategy to quantify the effect of environmental parameters in the design loads of OWT in North-Sea environmental conditions. Among these parameters uncertainty associated with the turbulence intensity, wave peak period have been propagated in the support's Damage Equivalent Loads (DEL), whereas mean wind speed, wave height and wind-wave misalignment considered as global parameters. Three sensitivity analysis techniques such as PAWN, Delta, and standardized rank regression coefficients (SRRC) are used to evaluate the total effect of the five key parameters on the DELs of IEA's 15 MW reference OWT. This analysis is conducted based on a proposed improved semi-probabilistic design model technique, which uses selective sampling to reduce the computational restraints of the OWTs environmental design space. The models resulting analysis shows a high impact of mean wind speed and wave height, however, on a local sub-categorized case, in different operational wind speeds, the turbulence intensity and wave peak period cause high variability in results, which is largely unrepresented in the current industry design models.

Keywords: Offshore wind turbine, Uncertainty Quantification, Sensitivity, Fatigue life, Structural Reliability, Remaining Useful Life.

1. Introduction

As the wind industry progresses to wind turbines of greater generation capacity at 15 MW and beyond, the corresponding structures required to support these assets are increasing in complexity due to increased loading requirements and changes in control systems to manage efficient operation (Velarde et al. (2020)). Whilst these structures increase in size the expectation of service life is increasing beyond 25 years; which is achieved through improved design and lifetime extension techniques.

1.1. *Lifetime extension practices*

Research around life extension of wind turbines structures is primarily focused on reactive and operational remaining useful life (RUL) estimations. RUL models are calculated with operational data from measured environmental conditions, which help forecast lifetime reliability. With RUL and operational maintenance, wind turbines can operate beyond their 20-year design life, however, there is awareness within design practice that structures are over designed for their operational and extreme environments. Offshore structures are influenced by various factors which contribute to this reserved extra life which is found during operation of the WTG assets. This is due to strict design standards and large imposed safety factors, alongside lighter lifetime loads due to lower site-specific conditions and milder utilization of the structures. In practice, lifetime extension is planned into structures after 10 or more years of operation through RUL and maintenance. However, investigation into the calculation of the reserved extra life at the design stage has been sparsely investigated and poses an opportunity for investigation. To assess the service life before operation, a comprehensive analysis of the design model, imposed safety factors and simplified environmental and structural parameters must be investigated.

1.2. *Structural design model and standardization*

Offshore wind turbine structures (OWTs) are exposed to a large array of environmental conditions, where designers are challenged to calculate realistic load conditions, which must represent the various possible failure modes. The most common failures in offshore support structures are plastic collapse, fatigue, excessive deflection, excessive vibration and buckling (Wang et al. (2022)). These are categorized into four limit states, ULS (Ultimate limit state), FLS (Fatigue limit state), ALS (Accidental limit state), and SLS (Service limit state), their definitions can be found in the IEC and DNV-GL design standard and in Wang et al.. However, it is commonly found that FLS is the design driver for OWT structures and impacts the design life of the structure (Velarde et al. (2020); Nispel et al. (2020, 2021); Wang et al. (2022)).

OWT's are highly sensitive to dynamic amplifications and fatigue damage, as the excitation frequencies resulting from the environmental loads of wind and wave approach the natural frequencies of the structure (Bhattacharya (2014); Bisoi and Haldar (2014); Rezaei et al. (2018)). In the design analysis, fatigue calculations involve an array of input parameters which characterize the environment, geometry and operational control conditions. These parameters are assessed in various operational conditions providing a representative response of the structure. This representation is measured to ensure the structure meets its service life of 20-25 years (Rezaei et al. (2018); Haldar et al. (2018)). In practice, these are done to the IEC and DNV-GL requirements, which encourage utilizing representative sea states and a semi-probabilistic approaches to the design space of wind and other environmental conditions. This involves simplifying the environmental conditions according to the design load cases, reducing the variability through discrete inputs, and reducing the design space to have a practical total analysis time for the project timeline. For example, wind speeds are binned at 2 m/s steps, with turbulence intensity taken as a 90th percentile ambient or effective additional value per wind speed, whilst sea states are taken as the mean average conditions of the wave height and peak wave periods per wind speed in 12 directional segments that represent the entire 360 degrees of directional loading. This approach has been identified to not reflect the true damage imposed on structures (Wang et al. (2022); Nispel et al. (2020)). Therefore it is necessary to find techniques which can better represent the true damage and impact of the environmental conditions.

In this study, a sensitivity analysis is conducted on the environmental conditions in the model space to verify the accuracy of a semi-probabilistic model and the impact of the parameters. The design model introduces a probabilistic approach for the design assessment of environmental conditions based on the design load cases recommended by the design standards, complemented with an improved global and local sampling scheme of the environmental parameters to capture the natural variability of such parameters while keeping the computational costs acceptable. Specifically, the wind speed and wave height space form the global sampling grid while the local turbulence intensity and peak wave period are local variables conditional to the global grid. This technique allows for a highly representative assessment of the stochastic sample space with reduced computational restraints as it decouples the variables correlation.

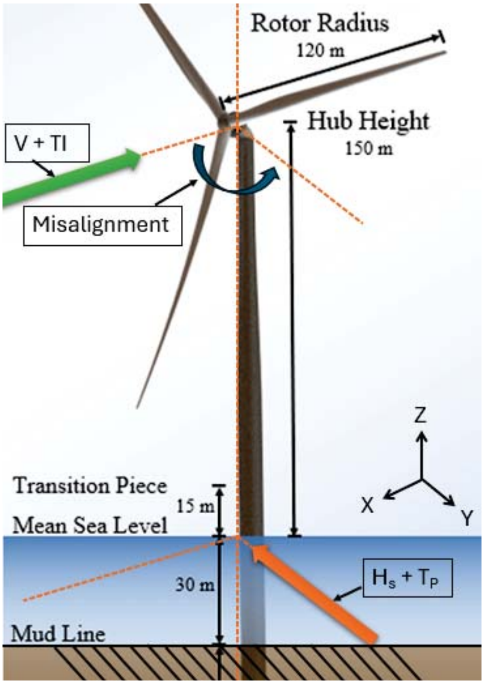

Fig. 1. Altered NREL 15 MW OWT Schematic with parameters marked

2. Methodology

In this study, a model was developed to investigate the sensitivity of environmental parameters and their representative time based equivalent damage on a 15 MW OWT (Gaertner et al. (2020)) reference turbine with a monopile foundation as shown in Fig. 1. This section describes the method used with the deterministic aero-elastic model and the sensitivity techniques used to measure the parameters influence on damage.

2.1. *Deterministic model*

2.1.1. *WTG design model*

The deterministic model is a combination of the open source code Turbsim and Openfast which have been developed by NREL, for academic and industry collaboration of innovation in wind turbine engineering (Jonkman et al. (2005); Gaertner et al. (2020)). Openfast allows an analyst to calculate the impact of wind turbulence on the blades and structural components, and to accurately account of turbine control systems in the above and below rated power conditions, alongside the ease of implementation of design load cases (DLC) in accordance of the IEC61400-1 (Jonkman et al. (2005); Nispel et al. (2021)). Turbsim creates the dynamic wind time series used in Openfast.

The NREL reference turbine's geometry and control system is unaltered in this design model, whilst the environmental conditions which are imposed on the structure in the time domain analysis are varied as the primary area of investigation. The 15 MW reference turbine (Fig. 1) has a hub height at 150m above sea level, with a monopile of 75m in length, 45m embedded below the soil, alongside a 15m transition piece between the tower and monopile. For the study a 30m localized site sea depth was used, and the monopile is fully fixed at the mudline. For further details refer to the technical report by Gaertner et al.. Turbsim was utilized to prepare time based dynamic wind profiles for 600 second samples, which were then used within the Openfast software to analysis the time based loading of the wind alongside other environmental conditions.

2.1.2. *Fatigue calculation*

In accordance with the IEC 61400-1 standards, the fatigue limit state is measured by the summation of the cumulative damage of all DLC's in correspondence with their probability of occurrence during the design life of the structure or component (IEC (2019b)). However, the primary influential fatigue damage accumulating DLC's are load cases, 1.2, 2.4, 3.1, 4.1, 6.4 and 7.2, as can be found in the IEC 61400-3. These DLC's represent the normal power production, shut down and park situations of a WTG, and lay in the central operational wind speed range. This study focuses on DLC 1.2 only, as the normal power production scenario.

In practice the total fatigue damage is calculated through either fracture mechanics methods or the S-N curve method (Wang et al. (2022)), with the use of classic Palmgren Miners rule (Miner (1945)) for stress counting. However, the NREL code and analysis software utilize the time based simulations for damage equivalent load

(DEL) instead of total damage, this is calculated by Eq. (1). DEL represents the equivalent total damage due to a loading block of stress or as a representative bending moment of a single amplitude stress with a given cyclic frequency.

$$DEL_{eq} = \left(\sum_i \frac{S_i^m N_i}{N_{eq}} \right)^{\frac{1}{m}} \quad (1)$$

In Eq. (1), S_i represents the moment stress magnitude range of the individual cycles, N_i represents the count of each stress range, N_{eq} represents the total number of cycles across the time frame and m is the Wohler exponent of the material, which for this study is 3 for steel. This technique is favorable as it indicates which DLC's are more damage inducing over a defined time. The resulting DELs are presented for the forces Fx, Fy, Fz, and moment forces Mx and My. Where z is the vertical axis, x is the primary wind direction of fore-aft movement and y is 90 degree to the x-axis as the side-to-side movement of the OWT.

2.1.3. *Environmental model and conditions*

In this study, the aim is to further investigate the impact of the environmental conditions on the NREL 15 MW offshore turbine DELs to identify and present a more robust fatigue damage calculation. The 5 key environmental parameters to be investigated are the wind speed, V; Turbulence Intensity, TI; Wave height, Hs; Wave peak period, Tp; and wave direction (wind-wave misalignment). In practice it is common to simplify and reduce the environmental variability of parameters assessed, to reduce the total analysis time required for iterative design and collaboration between OWT manufacturer and substructure designers. The wind and waves magnitude, frequency, period and direction (Hodgson et al. (2016)) are closely correlated at OWT sites, where the joint probability and correlation is measured at early site investigations to characterize the limit state design loads imposed on the OWT. However, instead of measuring every single combination of possible scenarios that a OWT can encounter, designers use simplified characteristic sea states per wind speed and wave direction combination. The sea states are chosen from the mean wave height and peak wave period ascertained during site investigation (Passon (2015)). This conservative approach reduces the samples of possible scenarios and neglects the interactions of scenarios deemed to have a low impact on the fatigue and structural integrity. This practice misrepresents the true wave climate, resulting in a misrepresented fatigue damage due to wave loading (Hodgson et al. (2016)). Similarly, the turbulence intensity is simplified from the stochastic variance at each wind speed to relative extreme or ambient turbulent percentages per DLC under investigation (IEC (2019a)).

For this study, only the primary dominant wind direction is used for a site, whilst the wave direction and directional misalignment is characterized by assessing six wave directions (0, 30, 60, 90, 120, and 150). The wave directions each represent a 30 degree segment, which, in line with the Upwind guidance from Fischer et al., can represent the lumped wave direction of two symmetrical wave directions' weighted probability. Thus this model analyzes the full 360 degree space using 6 segments of 30 degrees, thereby assesses six wind and wave direction cases. The wave heights, H_s, and peak wave period ,T_p, is taken according to the wind-wave direction correlations from the Hodgson et al. study, where H_s and T_p follow weibull distributions according to site conditions. The wind speed weibull distribution for the dataset is characterized by a shape factor of 8.92, a scale of 1.81, about a mean wind speed of 7.9 m/s, however, this distribution will only be used in future work on total DEL calculations of the stochastic space. For the wind speed, the area of interest is the operational region of the WTG between 3m/s and 21m/s, which contributes to upwards of 90% of the Weibull distributed wind speeds for all wind directions. The turbulence intensity , TI, is bounded by North Sea wind conditions, with ambient percentages between 4 and 40 % depending on the wind speed.

2.2. *Sampling space*

To assure the coverage of the entire sample space with limited number of samples, Latin hypercube sampling (LHS) was adopted as the statis-

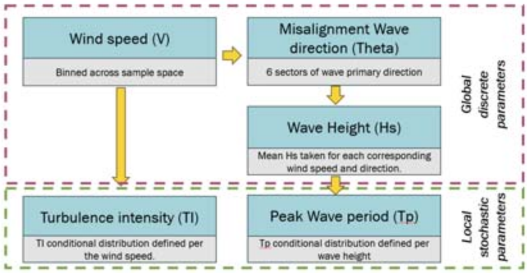

Fig. 2. Flowchart of Global local parameters

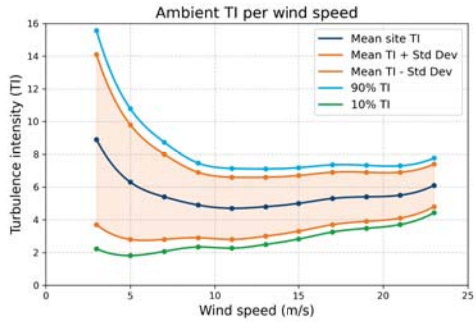

Fig. 3. Ambient TI across wind speed for the model

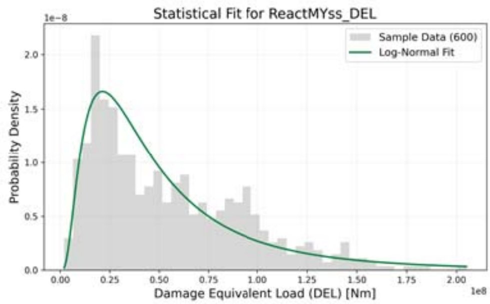

Fig. 4. DEL loads and log-normal trend line for MY reactive forces across sample space

tical sampling technique used to sample a test space with multiple uncertain input parameters. A LHS efficiently explores a multi-dimensional input space with each input evenly sampled across the space with a limited number of simulations and no duplication or bias to a specific region of the sample space. For this study of five environmental input parameters a multi-layered LHS sampling technique was used, utilizing a global-local mix, to isolate key discrete variables whilst assessing more empirically-derived distributions and impact of inputs which are linked by conditional stochastic relationships. On a Global level, the inputs are discrete inputs informed by environmental distributions, with 10 wind speeds identified as key binned wind speeds from the weibull distribution of wind occurrence. For each wind speed there are six corresponding wave directions and wave heights, where the wave height is a discrete input per wind speed and direction, seen in Table 1.

On a local level the inputs are taken from a probabilistic sample space of the conditional relationships identified between V and TI; and Hs and Tp. Where TI is characterized by the normal distribution related to the mean and standard deviation per wind speed bin, see Fig. 3. Whilst, the Tp is taken from the normal distribution of the Hodgson et al. study, see Table 2. For an overview of the local global sampling hierarchy see Fig. 2.

A LHS sampling of 600 samples across the defined sample space was created against common practice of 20000 or more cases. The new sampled space can be compared to the conventional techniques of wind binning used in IEC 61400-3, as it utilizes wind speed binning and a semi-probabilistic model, however increases accuracy of DELs with a realistic representation of the TI and Tp of the site.

2.3. *Sensitivity analysis*

The LHS sample and subsequent output DELs were then tested against the SRRC, PAWN, and Delta techniques to analyze and establish the impact of the 5 parameters on the output results of damage. SRRC was used to analyze the first order independent impact of each parameter on the system, using simple regression techniques. The PAWN sensitivity analysis was used for its effectiveness in complex and nonlinear models, where the analysis conducts a global analysis using the cumulative distributions. The PAWN distribution based sensitivity measures the input variables' impact on the output variables through a cumulative distribution method (Pianosi and Wa-

Table 1. Wind speed and corresponding Hs per wave direction.

Wind wave Misalignment	0-0 Hs	0-30 Hs	0-60 Hs	0-90 Hs	0-120 Hs	0-150 Hs
Wind Speed						
3	1.16	1.09	1.05	1.13	1.18	1.17
5	1.22	1.17	1.15	1.16	1.25	1.31
7	1.37	1.26	1.33	1.35	1.39	1.48
9	1.55	1.45	1.59	1.61	1.56	1.75
11	1.85	1.75	1.83	1.93	1.81	2.01
13	2.17	2.07	2.22	2.38	2.21	2.35
15	2.56	2.45	2.78	2.84	2.64	2.74
17	3.07	3.14	3.61	3.52	3.29	3.19
19	3.72	3.77	4.1	4.01	3.96	3.92
21	4.36	4.31	4.24	4.67	4.52	4.39

Table 2. Wave Height (Hs) and conditional Peak wave period (Tp).

Hs Bin	Tp mean	Tp std dev
0.0 - 0.5	2.445	0.646
0.5 - 1.0	3.283	0.825
1.0 - 1.5	4.056	0.863
1.5 - 2.0	2.147	2.081
2.0 - 2.5	5.339	0.912
2.5 - 3.0	5.726	0.933
3.0 - 3.5	6.434	0.769
3.5 - 4.0	5.932	0.826
4.0 - 4.5	3.389	2.089
4.5 - 5.0	5.810	0.689

gener (2018)). Finally, the Delta method, similarly measures the global impact through moment independence, analyzing the shape of the output distribution. The 3 methods were used together to verify the results and analyze both first order and global impacts on the system. It is common practice in the OWT industry to use the Sobol sensitivity technique which can be used for either first order or total order measurement, measuring the variance of the system inputs. This technique wasn't viable with the LHS sample spread, unless a larger sample was taken. PAWN was favorable in this circumstance for its robustness in system outputs with high extreme results, which are present in this model, which follows a log-normal DEL trend, see Fig. 4. The sensitivity analysis was conducted in two phases, 1) over the global 600 sample space and results and 2) over a reduced 4 parameter localized test per wind speed bin done with PAWN. These were both conducted to analyze both the overall large impacts and the finite impacts of the parameters in more concentrated scenarios. PAWN and Delta were used through the SALib analysis package, whilst SciPy was used for the SRRC analysis and statistical trend identification, all of which was conducted through python scripts.

3. Results and Discussion

3.1. *Sensitivity of the Environmental conditions on fatigue life damage*

The sample space output DELs fit a log-normal trend as seen in Fig 4, showcasing the highly variable magnitude of damage in a reduced sample space, within the OWT's operational conditions. This sample does not represent a true weighted probability distribution of a design sample space due to the binned wind speeds sampling used and lack of weighted averaging used for total DEL calculations, but allows a insight into the range of DELs expected. From the LHS and sensitivity analysis, Fig. 5 and Fig. 6 present the findings of the 600 sample space.

In the global overview, it was found that wind speed, V, has the highest impact factor in nearly all load responses at the monopile mudline, except for in My, where the Hs had a 0.1% larger impact factor, however Hs is correlated to V due to its discrete selection.

The reaction forces, Fx, Fy, and Fz were marginally impacted by TI and Tp. Mx was impacted by Tp more than TI, which can be attributed to the impacts of misalignment action causing larger side-to-side motions. Finally, the Wave direction impacted the Fy and Mx and was insignificant in all other reaction forces. These index results are consistent throughout the three tests, with the first order test having higher overall measure of impact, whilst the global measure of PAWN and Delta having lower corresponding impacts.

In contrast to the global models sensitivity test, the reduced localized test as seen in Fig. 6 across the wind speeds, highlights that when wind speed is removed as the governing parameter, the other environmental parameters more closely share influence on the DEL results. With TI being more influential across all DEL resulting forces, especially in higher wind speed scenarios. Hs, impacts low wind speed scenarios consistently, with reduced impact in high wind speeds, whilst Tp varies from case to case and would need a higher fidelity model to understand its impact in all localized regions. Similar to the global tests, wave direction is highly impactful in Mx and Fy forces. It can be seen that all 5 environmental conditions contribute to the DEL force reactions in the model and all must be correctly accounted for during design procedures. Minor variance of a parameter which is different during operation could vastly change the damage transferred through the structure. This becomes highly impactful when analyzing the localized regions of wind speed, where TI and Tp have a larger impact on DEL variability than assumed in conventional model techniques.

3.2. *Conclusion*

The study has analyzed the impacts of five key environmental conditions on the fatigue load and resulting damage equivalent loads for offshore wind turbine monopile substructures showing that wind speed and wave height are the largest impacting parameters causing damage in the operational state. Turbulence intensity and peak wave periods variability marginally impacts the overall damage, but when a localized sensitivity analysis is conducted in each wind speed, these parameters become more influential in the damage equivalent loads. This showcases that if incorrectly represented, turbulent intensity and peak wave period parameters can largely impact the localized regional damage, which when calculated across a structure's lifetime, could change the true representation of damage and misrepresent the impact of peak wave period and turbulence intensity during the design stages. This semi-probabilistic model with a LHS reduced sample showcases the high impact of intelligent sampling on analyzing the damage in DLCs by reducing computational time and utilizing statistical analysis. The obtained results shed light on the importance of data collection to reduce the uncertainty in the input environmental data at pre-construction stage to obtain more accurate design DELs.

Acknowledgement

The authors wish to acknowledge SSE and EPSRC for funding the study work under the grant number EP/R001472/1.

References

Bhattacharya, S. (2014). Challenges in design of foundations for offshore wind turbines. *Engineering & Technology Reference* (2014).

Bisoi, S. and S. Haldar (2014). Dynamic analysis of offshore wind turbine in clay considering soil–monopile–tower interaction. *Soil Dynamics and Earthquake Engineering 63*, 19–35.

Fischer, T., W. d. Vries, and B. Schmidt (2013). Upwind design basis, wp4: offshore foundations and structures.

Gaertner, E., J. Rinker, L. Sethuraman, F. Zahle, B. Anderson, G. Barter, N. Abbas, F. Meng, P. Bortolotti, W. Skrzypinski, et al. (2020). Definition of the iea 15-megawatt offshore reference wind turbine.

Haldar, S., J. Sharma, and D. Basu (2018). Probabilistic analysis of monopile-supported offshore wind turbine in clay. *Soil Dynamics and Earthquake Engineering 105*, 171–183.

Hodgson, T., N. Sampathkumar, and I. Cortizo (2016). Approach to wind wave correlation in coupled analysis of offshore wtg substructures. *Wind Europe Summit*.

IEC (2019a). Iec61400-1-2019 wind energy generation

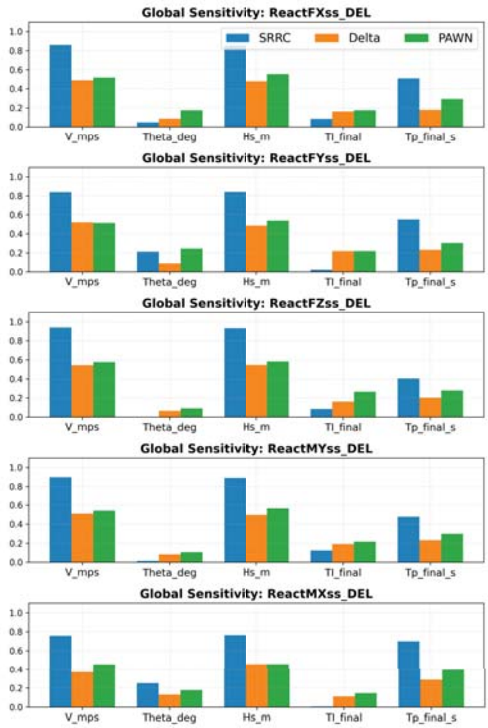

Fig. 5. Global Sensitivity plots of DEL loads per parameter

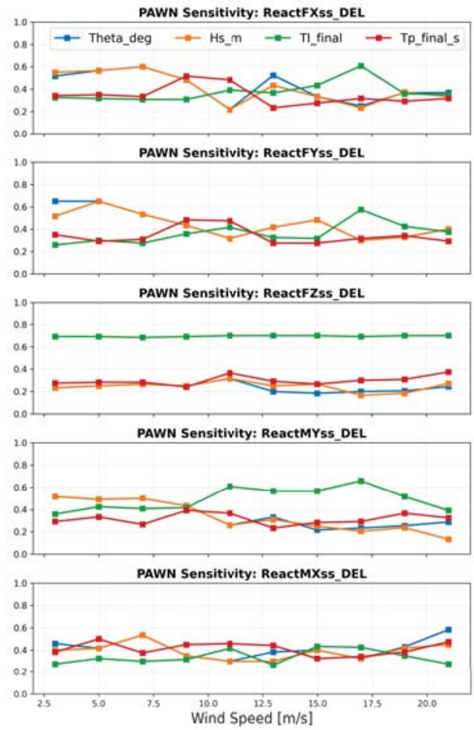

Fig. 6. Local wind speed regional PAWN Sensitivity plots of DEL loads per parameter

systems – part 1: Design requirements. Technical Report IEC 61400-1, International Electrotechnical Commission, Geneva, Switzerland.

IEC (2019b). Iec61400-3-1-2019 wind energy generation systems – part 3-1: Design requirements for fixed offshore wind turbines. Technical Report IEC 61400-3-1, International Electrotechnical Commission, Geneva, Switzerland.

Jonkman, J. M., M. L. Buhl, et al. (2005). *FAST user's guide*, Volume 365. National Renewable Energy Laboratory Golden, CO, USA.

Miner, M. A. (1945). Cumulative damage in fatigue.

Nispel, A., S. Ekwaro-Osire, and J. P. Dias (2020). Probabilistic analysis of the fatigue life of offshore wind turbine structures. In *Turbo Expo: Power for Land, Sea, and Air*, Volume 84249, pp. V012T42A004. American Society of Mechanical Engineers.

Nispel, A., S. Ekwaro-Osire, J. P. Dias, and A. Cunha Jr (2021). Uncertainty quantification for fatigue life of offshore wind turbine structure. *ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems, Part B: Mechanical Engineering 7*(4), 040901.

Passon, P. (2015). Damage equivalent wind–wave correlations on basis of damage contour lines for the fatigue design of offshore wind turbines. *Renewable Energy 81*, 723–736.

Pianosi, F. and T. Wagener (2018). Distribution-based sensitivity analysis from a generic input-output sample. *Environmental Modelling & Software 108*, 197–207.

Rezaei, R., P. Fromme, and P. Duffour (2018). Fatigue life sensitivity of monopile-supported offshore wind turbines to damping. *Renewable energy 123*, 450–459.

Velarde, J., C. Kramhøft, J. D. Sørensen, and G. Zorzi (2020). Fatigue reliability of large monopiles for offshore wind turbines. *International journal of fatigue 134*, 105487.

Wang, L., A. Kolios, X. Liu, D. Venetsanos, and R. Cai (2022). Reliability of offshore wind turbine support structures: A state-of-the-art review. *Renewable and Sustainable Energy Reviews 161*, 112250.