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ANNOTATED GUIDELINES FOR THE SIMULATION OF FLOATING OFFSHORE WIND TURBINES IN A REAL ENVIRONMENT

Francesco Papi
Alessandro Bianchini † *
Department of Industrial Engineering - Università degli Studi di Firenze
Via di Santa Marta 3, 50139, Firenze, Italy
Tel. +39 055 275 8773 - Fax +39 055 275 8755
alessandro.bianchini@unifi.it

ABSTRACT

In the case of floating wind turbines (FOWTs), international design standards currently leave a larger degree of freedom to engineers in the specification of the boundary conditions for turbine simulation and certification. This is due to fact that FOWTs are still a young technology, and standards are still evolving. To analyze offshore wind turbines and estimate parameters such as AEP, fatigue and extreme loads, site-specific reference environmental conditions need to be defined. Then, a probabilistic model of the installation site must be built in order to compute lifetime quantities. Finding a trade-off between simulation number and length and good long-term estimation of fatigue and ultimate loads, as well as the selection of relevant loading metrics requires a significant amount of research or experience in the field.

The current work aims at exploiting a procedure that was developed within the H2020 FLOATECH project and made available open source with this study to the scientific community, with the objective of addressing what is required to perform a load and performance evaluation of a FOWT in a real environment. A procedure to obtain environmental conditions if the ones available in the literature do not meet the designer's needs is first illustrated. Then, the most important parameters that need to be considered when performing an analysis of a FOWT are detailed; taking these into account and their corresponding metrics, a detailed guideline on how to define a suitable list of Design Load Cases (DLCs) is presented, as well as different methods to reduce the number of model evaluations deriving from the DLCs' list, and thus reduce computational time.

1. INTRODUCTION AND SCOPE OF THE STUDY

Floating Offshore Wind Turbines (FOWTs) are seen as one of the key technologies to sustain energy transition, since they could enable the exploitation of the high wind speed potential in deep seas [1]. While momentum in their industrial development is increasing, it cannot be neglected that they are still a quite novel technology that has not even coalesced yet into one (or even few) archetype [2,3]. In particular, it has been recently pointed out that one of the major factors hampering the development of FOWTs is the lack of assessed benchmarking cases and experimental data for validation of the performance of new design solutions [4]. While waiting for these benchmarks to be delivered, increasing attention is been given to the assessment of the accuracy of simulation models for FOWTs, as testified for example by the Collaborative Task 30 promoted by the International Energy Agency (IEA) [5]. In doing so, two levels of analysis can be identified. The more detailed one focuses on the single turbine under few, well-defined inflow conditions for wind and/or waves: these studies generally put emphasis on detailed studies of aero- or hydro-dynamics, e.g., to understand how these altered by the complex motions of a FOWT [6]. A second level of analysis is instead represented by studies about the expected performance of a turbine at scale in the real environment, in terms of Annual Energy Production (AEP) and loading (extreme and fatigue). These evaluations are extremely important for feasibility studies that could sustain investments in the sector. Due to the novelty of the technology, however, some aspects still need to be clarified.

The scope of the present study is then to critically elaborate the more significant proposals made so far in the literature and complement them with tailored procedures in order to define a complete framework that each research can use to simulate a FOWT in realistic conditions. The possible applications of such a framework are many, ranging from production assessment of a specific turbine design in a site, to comparative analyses of different concepts or benchmarking of simulation codes. This latter application is indeed the one that drove the conception of the present study, which bases on the European project FLOATECH [7]. In this context, the accuracy of three different pieces of software for FOWT simulation, including the new QBlade-Ocean [8], needed to be assessed. More specifically, the present study aims at helping the reader in:

- defining a complete set of *met-ocean conditions* (including wind speed, significant wave height, wave peak spectral period, and wind-wave misalignment), through which the behavior of a FOWT can be determined in terms not only of performance but also of extreme and fatigue loading (Section 2);
- preparing a list of *Design Load Cases (DLCs)*, among which all relevant cases to describe exhaustively the performance of a turbine or to compare different designs can be found (Section 3);
- selecting proper *metrics* for individual or comparative performance assessment (Section 3);
- defining the correct *number of simulations* needed to suitably cover the selected space of investigation with the least computational effort (Section 4).

2. DEFINING MET-OCEAN CONDITIONS

It is well-known that the environmental conditions wind turbines experience during operation are strongly non-deterministic. This consideration is even more relevant for modern multi-MW machines, whose blades exceed the atmospheric boundary layer, facing unprecedented inflow conditions [4]. In the case of offshore turbines, moreover, specific atmospheric phenomena are also to be accounted for, like for example tempests, marine jet flows, tornadoes, etc. [9]. While these phenomena have not been addressed in this study, and scarcely analyzed in the literature yet, they prove how much interest must be reserved to the characterization of the expected operating conditions. Despite the above, engineers need a way of estimating both fatigue and extreme loads even in such a non-deterministic design space. This need is addressed by creating a statistical model of the installation site through a stochastic representation of environmental variables, in which events with high probability of occurrence are fatigue-driving while the tails of the probability distributions can be used to estimate the likelihood of those weather events that cause extreme structural loading [10].

In the case of onshore wind turbines, design standards (e.g., [11], the aleatory variable is mainly the 10-minute-averaged wind speed at hub height only, since turbulence is determined as a function of it. Furthermore, to promote standardization of wind turbine designs, a series of design *classes* are prescribed, in each of which the long-term wind speed distribution is assumed to follow a Raileigh probability density function (PDF) with a prescribed mean, and a deterministic law is prescribed for turbulence intensity.

When moving offshore, however, the situation becomes more complex, since wind turbines are subject contemporarily to varying inflow and sea conditions, or, in other words, to complex *met-ocean conditions*. Wind is characterized based on speed and direction (U), with this second parameter being previously neglected assuming that the wind turbine can yaw, and the substructure is axisymmetric. Therefore, the wind speed direction distribution can be used to account for the locations on the substructure cross-section where most damage is recorded. On the other hand, an individual sea state can be modelled with three aleatory variables, namely the mean amplitude of the highest third of the waves (significant wave height H_S), the peak spectral period of the waves (T_P) and the mean wave direction. If we combine wind and wave direction by defining wind-wave misalignment (M_{WW}), a generic offshore site can be statistically modelled with four aleatory variables U, H_S, T_P, M_{WW}. As recently discussed by [10], this approach has some limitations like, for example, the inability of modeling two or three-peak wave spectra [12]. In the case of FOWTs, moreover, condensing wind and wave direction into the only M_{WW} implicitly assumes that the floater and mooring lines are symmetrical, which is often not the case. In fact, similar to onshore turbines, only if the turbine is able to yaw and the substructure is axisymmetric, the mean wind and wave directions can be neglected and synthesized in the M_{WW} parameter.

To date, design classes are not prescribed for any type of offshore wind turbine. Although the need for such standardization is acknowledged and encouraged in the DNVGL-SST-0119 design standard [13], the designer is required to define a suitable class for the design of the machine and verify the design for the specific installation site of choice. This means that, in the case of FOWTs, each turbine-floater combination has to be verified in a joint probabilistic model of the site-specific installation conditions. This can provide a representation of the long-term probability distributions of the four variables under consideration, while extreme cases can be defined be means of an environmental contour [14].

2.1 Literature case studies

Suitable datasets to build environmental contours for FOWTs (thus referring to sites with deep waters – approximately 100 to 200 m deep) are still scarce in the literature, mainly because high-quality, long-term measurement of meteorological and sea conditions are required as inputs. An overview of the most useful ones has been recently proposed in [10]. Among others, Stewart et al. [15] recently proposed some generic sites for researchers to use based on the elaboration of data referring to sites off the coasts of the United States. The approach used by these authors derives conditional distributions based on data bins; this in turn can make the creation of environmental contours tricky. Li et al. [16] defined long-term probability representations of five European sites based on hindcast data; in their dataset, however, wind-wave misalignment is not considered. Authors report 3-D contours of U-H_S-T_P that are suitable to derived extreme met-ocean conditions in a parked configuration for FOWTs. However, Severe-Sea-States (SSS) in operational conditions cannot be derived without requiring additional processing. The EU-funded COREWIND [17] and LIFEs50+ [18,19] project provide processed met-ocean data. In both of them, unfortunately, the resolution of the variables is often coarse and, since the post-processing has already been performed, it is not possible to derive additional quantities that may be of interest.

2.2 A comprehensive procedure to derive met-ocean conditions

If one needs to go beyond existing datasets or explore new installation sites, a procedure to obtain met-ocean data for a given offshore location and process it is necessary. Such a procedure is ultimately needed to obtain a long-term description of the site in terms of marginal conditional PDFs for U, H_S, T_P and M_{WW} and is proposed in the following. The procedure has been conceptualized by the same authors in [10] (where all details about implementation can be found), but it is here briefly explained since it represents one of the conceptual steps of the global guidelines proposed for FOWTs.

The procedure builds upon open-source tools and datasets and can be replicated or modified to be integrated into existing pre-processing pipelines. Raw hourly data of U, H_S, T_P and wind and wave direction can be obtained, in principle, from any source, but in [10], the ERA5 database [20] is suggested. This re-analysis database contains hourly data on a 30 km grid from 1979 onwards. It is available open-source, it has been extensively validated in many independent studies such as [21–23] and over forty years of data are available.

Once the raw data is available, a statistical hierarchical model of the installation site needs to be built. Such models are able to represent the long-term probability distribution of the installation site in terms of the four environmental variables that are considered. These models are used when the aleatory variables are not statistically independent, such as the four variables that define the long-term met-ocean conditions of an offshore site. The PDF of the combination of the four environmental variables is defined as in Eq. 1:

$$f_{U,H_S,T_P,M_{ww}}\left(U,H_s,T_p,M_{ww}\right) = f_U(U)f_{H_s}(H_s|U)f_{T_P}\left(T_p\middle|H_s\right)f_{M_{ww}}(M_{ww}|U) \tag{1}$$

f_U, f_{H_s}, etc. are the marginal PDFs. f_{H_s}, f_{T_P}, and $f_{M_{ww}}$ are also conditional as they depend on another aleatory variable. A hierarchical model can in general be built in any modern high-level programming language. In [10], the open-source Python package Virocon [24] is used to build the hierarchical model. Once the marginal PDFs are chosen, they are fit to the gathered data and the hierarchical model is build. How well the model fits the data depends on the chosen marginal PDFs. Haselsteiner et al. [25] proposed marginal PDFs and dependence functions that are, sometimes loosely, related to the physics that govern the interactions between the environmental variables. These dependence functions are used in [10], but could in principle be replaced with any function available in Virocon.

After the hierarchical model is built, it can be used to find expected values of H_s and T_p conditioned on U, defining the Normal Sea State (NSS) for extreme load calculation, as defined by international guidelines [26]. The model can also be used to compute the probability of each combination of the aleatory variables, which is necessary for fatigue loads, as discussed in Section 4. For some DLCs, standards require the definition of an environmental contour, which is the combination of two or more of the environmental variables with a certain return period, typically one of fifty years. In [10], as recommended by current standards, the IFORM method is used to derive U-H_s environmental contours. This is not the only method available in Virocon, where for instance the ISORM method is also available. The environmental contour depends on the method that is used to compute it and on the hierarchical model of the installation site and is not independent of the choice of marginal PDFs. Haselsteiner et al. have conducted various comparative benchmarking studies [27,28] in which various methods for environmental contour calculation are compared. While different methods have fared better or worse depending on the specific examined site, the marginal PDFs proposed in [25] and used in [10] fared well overall.

Finally, combinations of the environmental variables with a return period of one or fifty years are also relevant for the Extreme Sea State (ESS). Current design standards are vague regarding how these conditions shall be defined, for instance it is simply mentioned that the most damaging value of T_p must be chosen for a given combination of U and H_s, without any guideline on how it shall be calculated. Valamanesh [29] provides an interesting discussion on the various possible ways of defining ESS conditions, and the implication that they may have on extreme loads. As explained in [10], ESS conditions lie on the environmental contour with the corresponding return period. For instance, for a U-H_s contour, the crosses in Fig. 1 fulfill this requirement. Selecting these points as ESS conditions requires to evaluate the wind turbine model in both conditions for each contour, since for FOWTs one variable is not clearly more important than the other when it comes to extreme loads. To comply with both IEC and DNV standards (presented in Section 3.1), for each point multiple suitable T_p must be considered, to include the one that causes the highest damage on the structure. If the number of required model evaluations needs to be kept at a minimum, the two extreme conditions can be combined in order to simulate the points that are indicated by the red and blue dots in Fig. 1. The expected value of T_p in these conditions is used. This is generally a conservative assumption, as the highlighted point lies on an environmental contour with a return period greater than the desired one. Therefore, it is advisable for code-to-code comparisons or preliminary design iterations to limit the number of simulations to perform, but should be used with caution, as Valamanesh has shown that choosing this point may not always result in the highest ultimate loads for all the components [29].

3. DLCs AND METRICS

In order to evaluate the performance of a FOWT in realistic inflow conditions, the long-term definition of an installation site is needed, defined in previous Section 2. This has to be coupled with a set of design conditions relevant for performance evaluation and ultimate and fatigue component loading, which is addressed in this section.

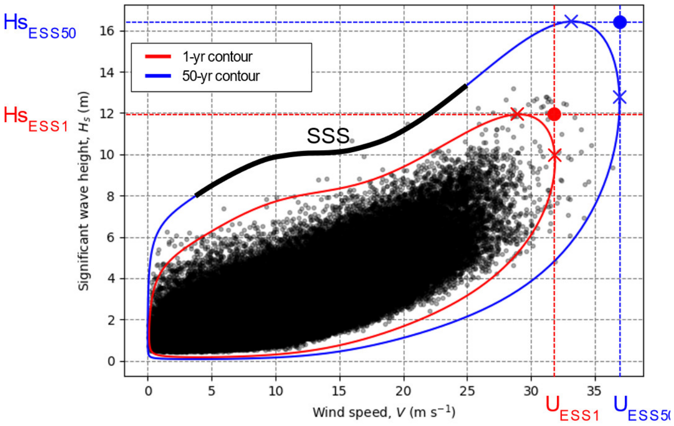

FIGURE 1: WIND SPEED – SIGNIFICANT WAVE HEIGHT ENVIRONMENTAL CONTOURS COMPUTED WITH IFORM METHOD IN VIROCON FOR THE WEST OF BARRA SITE. 1-D EXCEEDANCE VALUES OF WIND SPEED AND SIGNIFICANT WAVE HEIGHT IN DASHED LINES, CORRESPONDING TO ESS CONDITIONS. IMAGE FROM [10].

3.1 Indications from the standards

To define a set of design situations relevant for FOWT loading, international design standards, such as IEC 61400-3 Part 2 "Design requirements for floating offshore wind turbines" (2019) can be used [30], which complements the more general standard on offshore wind turbines [26]. This part of IEC 61400, which in fact represents a technical specification, specifies additional requirements for assessment of the external conditions at a FOWT site and specifies essential design requirements to ensure its engineering integrity of FOWTs, intended as the entire system including the five principal subsystems, i.e., the RNA, the tower, the floating substructure, the station-keeping system and the on-board machinery, equipment and systems that are not part of the RNA. The technical specification addresses in detail five types of floating substructures (ship-shaped structures and barges, semi-submersibles, spar buoys, and tension-leg platforms/buoys), and generally covers other floating platforms (at the time of writing more than 50 floater concepts are under consideration [31]) intended to support wind turbines, for which case-specific analyses are suggested. Another widely adopted standard for the design and certification of FOWTs is DNV ST-0119 [13]. Similarly to the IEC series discussed previously, this document complements the more general DNV ST-0437 standard [32], which is intended for bottom-fixed onshore and offshore machines. Both the IEC and DNV standards are directly applicable to floating structures with one single horizontal axis turbine, while again additional considerations might be needed for multi-turbine units on a single floating substructure or vertical-axis wind turbines. Overall, it is reasonable to hypothesize that standards will need to evolve in the next few years, along with the evolution of the technology. This also testifies how much interest is posed on the simulation of FOWTs.

Beyond turbine definition, the key element of interest for the present study is how standards manage the cases that need to be considered for performance assessment. Analogous to onshore turbine, DLCs are defined also for offshore ones; in this case, a DLC is the combination of a certain operating condition (power production, parked, fault, etc...) with a certain environmental condition, like the Normal Sea State (NSS), Severe Sea State (SSS), Extreme Sea State (ESS), etc... DLCs are intended for wind turbine load calculation and certification: the process through a third party certifies that the machine is built according to the standard. In particular, the technical specifications IEC 61400-3-2 and DNV-ST-0437 add a table of DLCs specific for FOWTs (namely, for IEC 61400-3-2 DLCs 2.6, 4.3, 9.1-9.3, and 10.1-10.3) that aim at evaluating the performance both in normal operation and parked conditions, with a special focus on those less-frequent, but high-demanding, conditions. Among others, the design must maintain structural integrity from all hazards during the planned lifetime, including ultimate loads for 50-yr extreme events and fatigue loads for a lifetime typically of 20-yrs. Evaluating fatigue loads is particularly critical. In fact, if one accounts for all environmental variables (Section 2.2) and for the needed probabilistic approach that involves multiple seeding for each simulation, a complete coverage of the design space would lead to an almost intractable problem involving several tens of thousands of simulations that needs somehow to be contained.

3.2 Selecting DLCs

When focus is not strictly on turbine certification but, for example, on the benchmark of different concepts/designs [33] or simulation tools like in FLOATECH [34], the full design spectrum prescribed by the standards can be limited to a subset of DLCs that, however, need to provide a good estimation of fatigue and extreme loads. In fact, even in a comparative study, the validity of the outcomes may be undermined if the estimates of fatigue and extreme loads are far from those obtained during a certification process. In recent years, some authors have attempted load calculations on FOWTs. One of the first examples is the work by Jonkman and Buhl [35]. Here, a subset of power production, power production with occurrence of fault and parked DLCs is considered. Namely DLCs 1.1, 1.3, 1.4, 1.5, 1.6, 2.1, 2.3, 6.1 and 6.2 are considered. On the testcase that was considered (NREL 5MW mounted on the ITI Energy Barge concept), most extreme loads were found in DLC 1.1, 1.3 and 1.4. Ramachandran [36] presents the DLCs that were used in the H2020 Project LifeS50+ for the evaluation of four floater concepts, two semi-submersibles, one spar-buoy and one tension-leg platform. The list includes the DLCs simulated by Jonkman and Buhl with the omission of DLCs 1.5 and 2.1. Finally in the load evaluation of the IEA 15MW RWT in a floating configuration, Allen et. al. [37], use a subset of IEC61400-3 DLCs defined based on experience. The subset includes the DLCs of the previous studies but further reduces the subset, also not including DLC 2.3.

Jonkman and Buhl, as well as Ramachandran, include DLCs where faults of some components are simulated. These DLCs are typically not very computationally expensive, as they comprise of a low number of simulations. Therefore, although in the work of Jonkman and Buhl they did not result in being critical DLCs from a loading standpoint, they should be included, if possible, in the load evaluations. Especially when comparing successive design iterations, they could result in unforeseen extreme loads that may make the design improvements irrelevant. Including these DLCs is however not always easy: many wind turbine simulation packages rely on external control libraries for these fault cases and finding open-source controllers that are able to simulate faults is not always easy. In code-to-code comparative analysis especially, this can be an important stumbling block.

Upon synthesis of the aforementioned studies, a list of DLCs is proposed that is thought of use in all cases in which a code-to-code comparison has to be carried out. It comprises of DLCs 1.2, 1.3, 1.4, 1.6, 6.1, 6.3 and 6.3. Similar to Ramachandran, DLCs 1.5 and 2.1 are not considered. In addition, no fault cases are considered, as was done by Allen et al. DLC 1.1 was also not considered as it was considered superfluous with respect to DLCs 1.3 and 1.6, which have more severe turbulence and wave conditions, respectively. DLC 1.2 was added to the list for an estimation of fatigue loads, while DLC 6.2 was also included in order to evaluate the effect of inflow from multiple directions on a FOWT. If fault cases can be included in the comparison, DLC 2.1, that is simulated by Jonkman and Buhl and included in the LifeS50+ project, should be added to the list.

The proposed DLCs are summarized in Tab. 1.

3.3 Proposed metrics

Specifying a set of parameters that are relevant in the analysis of FOWTs is difficult as they depend on the specific task at hand. In this section, focus will be put on some metrics that should be considered, and that are critical to component design from a structural standpoint. General performance can be evaluated by observing sensors such as rotor speed and power. The INNWIND-EU report by Chaviaropoulos [38] specifies relevant parameters to use in the evaluation of innovative component designs. They can be summarized as follows:

- Blade root bending moments and blade tip-to-tower clearance
- Stationary hub (shaft) bending moments and forces
- Yaw bearing bending moments
- Tower base fore-aft bending moments

According to the authors, these load sensors are critical to the design of the blades, tower, foundation, yaw bearing, mainframe, pitch actuation mechanism, gearbox.

In addition to these load sensors, on a FOWT inertial and gravitational forces caused by motion of the floating structure introduce relevant loads, especially on components such as the tower and the yaw bearings. To separate the various loading sources and gain a better understanding of the mechanisms that are generating a specific extreme or fatigue load, it is in our experience useful to analyze:

- Platform pitch and roll. These metrics are important for system stability. Some guidelines on allowable limits to these metrics is provided by Ramachandran in [36]. Moreover, as these two sensors increase gravitational forces exert a bending moment on the tower and a shear force on the yaw bearing.
- Nacelle translational acceleration. Similarly to pitch and roll, maximum limits on values of this sensor are often set as design feasibility constraints [36]. These metrics are indicative of the inertial forces on the nacelle caused by the combined displacements of the foundation and tower deflection. These inertial loads act directly on the tower and yaw bearing as reaction forces.
- Aerodynamic thrust and torque. These metrics are useful to estimate the contribution of aerodynamic loads.

In addition, it is useful to analyze platform translational displacements, as there may be constraint on how much the FOWT is allowed to move, and mooring line tensions, as they are useful for mooring system design and allow for identification of slack-line events, if any.

The influence of the control system on the overall performance and stability of the system must also be carefully considered. In fact, in a FOWT, an incorrectly tuned pitch controller can lead to system instability, as shown by Larsen and Hanson [39] and Bredmose et al. [40]. Therefore, if system stability is of concern, at a minimum, blade pitch and platform pitch should be monitored closely. In summary, all the above metrics are thought of as crucial for component and system design.

TABLE 1: DLCs USED IN THE FLOATECH PROJECT [37].

DLC	**wind**		**waves**									
	model	**speed**	**model**	**height**	**period**	**direction**	**dur.**	**seeds/ws**	**yaw**	**n° ws**	**sims**	**type**
1.2	NTM	Vin-Vout	NSS	-	-	MUL	1800	1	0,10°	11	504	F
1.3	ETM	Vin-Vout	NSS	E[Hs|Vhub]	E[Tp|Hs]	COD	1800	9	0, +-10	11	99	U
1.4	ECD	Vr +- 2 m/s	NSS	E[Hs|Vhub]	E[Tp|Hs]	COD	600	-	0	6	12	U
1.6	NTM	Vin-Vout	SSS	Hs,SSS	E[Tp|Hs]	COD	3600	9	0, +-10	11	99	U
6.1	EWM50	V50	ESS	Hs50	E[Tp|Hs]	0°, +-30°	3600	2	0, +-10	1	12	U
6.2	EWM50	V50	ESS	Hs50	E[Tp|Hs]	-	3600	2	0,45,90 135,180	6	12	U
6.3	EWM1	V1	ESS	Hs1	E[Tp|Hs]	0°, +30°	3600	2	0, +-20	1	12	U

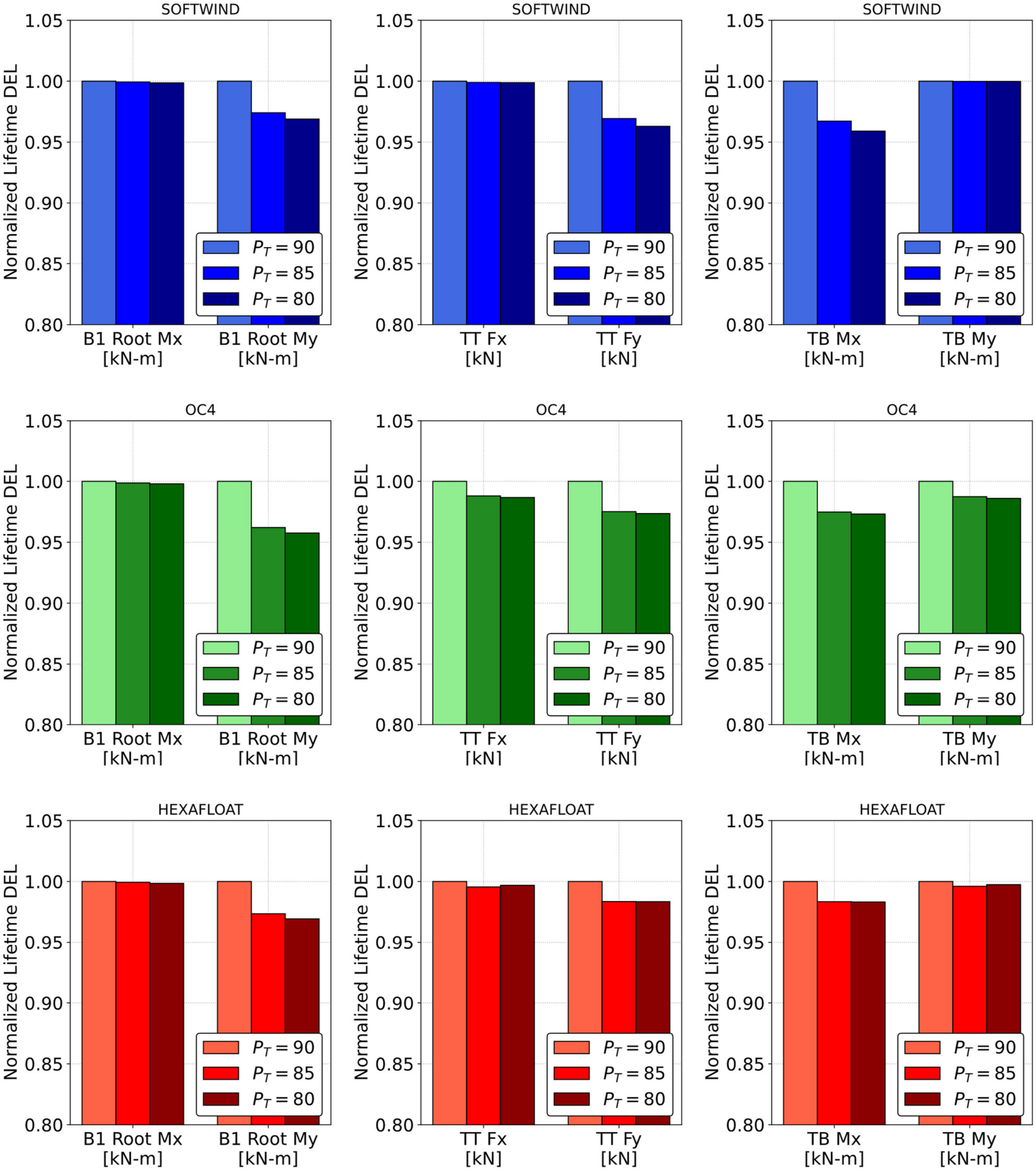

FIGURE 2: NORMALIZED LIFETIME DELs FOR THE THREE LOAD CASES ANALYZED IN [29] CONSIDERING 90%, 85% AND 80% COVERAGE OF THE PROBABILITY SPACE. LIFETIME DELS CONPUTED USING MLIFE [36], WITH 528734782.5 EQUIVALENT CYCLES.

TABLE 2: BIN RANGES AND WIDTHS. ADAPTED FROM [10].

Parameter	Range	bin width IEC	bin width
U (m/s)	4-26	2	2
H_S (m)	0-14	0.5	2
T_P (s)	3-21	0.5	2
M_{WW} (°)	-180 - 180	15	60
total bins	-	266112	4158

4. SELECTING SIMULATIONS

As discussed in Section 3, the DLCs that are selected for a specific analysis need to provide a good estimation of fatigue and extreme loads. In turn, simulations in selected DLCs do not need strictly to consider the full design spectrum in many applications beyond industrial turbine certification. In these cases, a balance between the number of computations to run and the coverage of the wind turbine design space needs to be struck.

In particular, in order to evaluate fatigue loads, multiple sea states need to be simulated. Loading on FOWT components needs to be evaluated for every environmental condition the turbine could possibly be operating in during its lifetime. Once a fatigue estimation is obtained for each environmental condition, the various estimates are combined based on their probability of occurrence and Lifetime Damage Equivalent Loads (DELs) are computed. Not every combination of the environmental variables can be simulated. Therefore, the design space is divided into a series of bins. The aero-servo-hydro-elastic model of the wind turbine in examination must then be evaluated for a significant enough amount of time within each bin to obtain an estimation of the fatigue loads for the given bin. IEC 61400-3 [26] provides guidelines to calculate bin size. The suggested bin sizes are shown in Tab. 2, which however shows that they would result in an excessive number of bins that need to be considered to cover the design space.

Stewart [41] analyzed various possible strategies to reduce the number of required bins. The methods that are proposed are as follows:

- Bin reduction: an increase in bin size reduces the total number of bins and thus the number of model evaluations required;
- Probability sorting: bins are sorted in order of increasing probability. The most likely ones are valuated first, each bin until a convergence of the desired fatigue loads is reached. The probability for each bin is equal to its share of the total probability weighted by the probability of each bin;
- Response surface: a least-squares best fit surface that relates a given DEL to the input met-ocean conditions is found using a limited number of simulations. The response surface can then be used to rapidly evaluate the fatigue loads in the entire design space;
- Genetic algorithm: through a genetic algorithm, a functional fit of the DELs of interest is created from a limited number of bins. The n-dimensional fitting surface is then used to predict DELs over the turbine design space.

If compared to a complete evaluation of the design space, the bin reduction and probability sorting methods have shown good results, being able to reduce the number of required simulations while maintaining good prediction capability of DELs. The genetic algorithm, which is more complex than the previous two methods, also showed good results, whereas the response surface method did not perform as well. When using a response surface method, one must keep in mind that the shape of the response surface is highly dependent on the specific load sensor that is being analyzed. Therefore, a n-order response surface, which may be a good fit for one load sensor, may not be the same for another. Indeed, non-linear behavior is often quite challenging to capture with a response surface, possibly explaining this observation.

Inspired by Stewart's findings, in the FLOATECH project a combination of the bin reduction and of the probability sorting methods was used. First bin size is increased. A fairly aggressive increase in size is used to limit the number of simulations as much as possible. Then the least likely bins are eliminated from the simulation list, until a certain threshold in terms of total probability is reached. We aimed to reach more than 90% coverage of the probability space. We also checked that the probability of the bins between cut-in and cut-out wind speed was above 90% of the total probability considering wind speeds between cut-in and cut-out. By combining the two methods, the number of bins was greatly reduced, limiting them to 252. The threshold of 90% was determined from speaking to industry contacts and is based on experience rather than on previous studies. The large reduction in the number of bins was necessary in the FLOATECH project as some computationally intensive design tools were used, and computational resources available within the project were limited. A limited number of bins can be considered when:

- *Comparison of design codes or turbine components in the same met-ocean conditions*: if a comparative analysis is performed it is generally more important to simulate as much as possible of the design space, at the expense of bin size;
- *Preliminary load assessments:* during the first design iterations it is reasonable to try to limit computational cost as much as possible while maintaining reasonable estimation of fatigue loads.

All this considered, it is interesting to evaluate if the 90% threshold can be reduced, limiting the number of bins even further. In Fig. 2 normalized lifetime DELs computed for various testcases considering 90%, 85% and 80% coverage of the total design space probability are shown for the three testcases that were used in the FLOATECH project. The test cases are described in [34] and are the DTU 10MW RWT mounted on the SOFTWIND spar platform and on the HEXAFLOAT two-piece platform recently proposed by Saipem®, and the NREL 5MW RWT mounted on the OC4 semi-submersible floater. The values shown in Fig. 2 are also reported in Tab. 3 for a more quantitative comparison. All the data shown is calculated with QBlade-Ocean and Raw data is available publicly (10.5281/zenodo.7254241).

TABLE 3: DIFFERENCES IN LIFETIME DELs.

Label	Units	90	85-90 diff. (%)	80-90 diff. (%)
SOFTWIND				
B1 Root Mx	kNm	1.91E+04	-0.07%	-0.14%
B1 Root My	kNm	2.03E+04	-2.59%	-3.11%
TB Mx	kNm	7.96E+04	-3.28%	-4.10%
TB My	kNm	6.94E+04	-0.02%	-0.02%
TT Fx	kN	5.51E+02	-0.10%	-0.12%
TT Fy	kN	5.90E+02	-3.07%	-3.70%
HEXAFLOAT				
B1 Root Mx	kNm	1.85E+04	-0.07%	-0.16%
B1 Root My	kNm	1.66E+04	-2.65%	-3.07%
TB Mx	kNm	8.83E+04	-1.66%	-1.68%
TB My	kNm	8.55E+04	-0.39%	-0.26%
TT Fx	kN	6.37E+02	-0.45%	-0.31%
TT Fy	kN	6.63E+02	-1.65%	-1.66%
OC4				
B1 Root Mx	kNm	6.36E+03	-0.13%	-0.20%
B1 Root My	kNm	6.57E+03	-3.79%	-4.24%
TB Mx	kNm	1.13E+04	-2.52%	-2.68%
TB My	kNm	1.86E+04	-1.26%	-1.40%
TT Fx	kN	2.14E+02	-1.20%	-1.33%
TT Fy	kN	1.21E+02	-2.48%	-2.64%

In the example shown in Fig. 2, 253 bins are necessary for 90% coverage of the probability space, 198 for 85% and 166 for 80%, a reduction in bin number and thus computational cost of 21% and 34% respectively.

As shown in Fig. 2, the value of the normalized 85% and 80% DELs with respect to 90% depends on the load sensor, and no general conclusions can be drawn. This depends on the specific simulations that are removed. For each wind speed, simulations with the highest or lowest H_S, T_P and M_{WW} are typically the least probable, and so are simulations with high wind speeds. Although not very likely, if these conditions introduce high fatigue loading on the structure, their removal may introduce bias in the Lifetime DELs. Moreover, while some general trends can be observed for all the platform designs, the magnitude of the normalized DELs with respect to the 90% DEL are case-dependent.

For some load sensors, such as yaw bearing fore-aft shear force (TT Fx) and blade root edgewise bending moment (B1 Root Mx), an estimate of Lifetime DELs with an error close to or below 1% can be achieved with significantly less simulations by considering 80% of the probability space.

To better understand where the differences are coming from, in Fig. 3, 1 Hz DELs grouped by wind speed are shown for the OC4 testcase. The other test cases are not shown for brevity. B1 Root Mx fatigue loads are mostly driven by gravity and are fairly constant. In addition, this load sensor is not strongly influenced by H_S, T_P or M_{WW}, and therefore low-likelihood bins can be removed without influencing Lifetime DELs significantly. A similar conclusion can be drawn for TT Fx. DELs of this load sensor show strong dependance on wind speed up to rated. Past rated wind speed, this load continues to increase due to the increase in mean H_S, and the contribution of in plane cyclic loads as the blade pitches, but not with the same magnitude.

On the other hand, for other load sensors, which like rotor thrust have a strong dependance on aerodynamics, such as blade root flapwise moment (B1 Root My), larger decreases are noted.

Interestingly, DELs computed with 85% total probability are closer to those computed with 80% than to those with 90% total probability. As shown in Fig. 3, B1 Root My increases as wind speed increases, and thus the removal of many 23 m/s and 25 m/s mean wind speed bins that are absent in both the 85% and 80% simulations, has an impact on this load sensor.

Tower side-side DELs, such as TT Fy and TB Mx, depend strongly upon significant wave height. The removal of bins with high H_S has an impact of Lifetime DELs, which are up to 2.7% lower for TT Fy in the OC4 testcase. Prediction with 80% and 85% coverage are close because many of the same high-H_S bins with 17 m/s, 23 m/s and 25 m/s mean wind speed are removed, as shown by the lower or absent mean DELs at these wind speeds in Fig. 3.

Finally, fore-aft tower base bending moment DELs are within 1.4% of the 90% case for all three testcases.

The analysis that was provided in this section is not without limitations. Firstly, DELs computed with 90% coverage of the probability space do not correspond to DELs computed considering the entire design space. Ideally this work can be extended to include higher than 90% coverages of the design space. To this end, it is interesting to note that when less of the design space is considered, according to the probability sorting method, the bins that are simulated are a subset of those that would need to be simulated if a higher percentage of the design space was evaluated. Therefore, a good practice that could be employed is to start from a lower coverage of the probability space and increase it in steps until the desired convergence is reached on the Lifetime DELs of interest. Based on the presented results, however, we suggest that at least 90% coverage of the design space is considered during such a convergence analysis. In fact, for many load sensors (Fig. 2), the difference in Lifetime DELs from 80% to 85% is smaller than the 90%-85% difference, therefore stopping at 85% coverage would lead one to erroneously believe that convergence is reached. It is interesting to point out that non-linear convergence rate is also observed in the work of Stewart [41]. Another limitation of this study is that zero-mean DELs with no Goodman correction are considered, effectively ignoring the effect of mean load on fatigue damage.

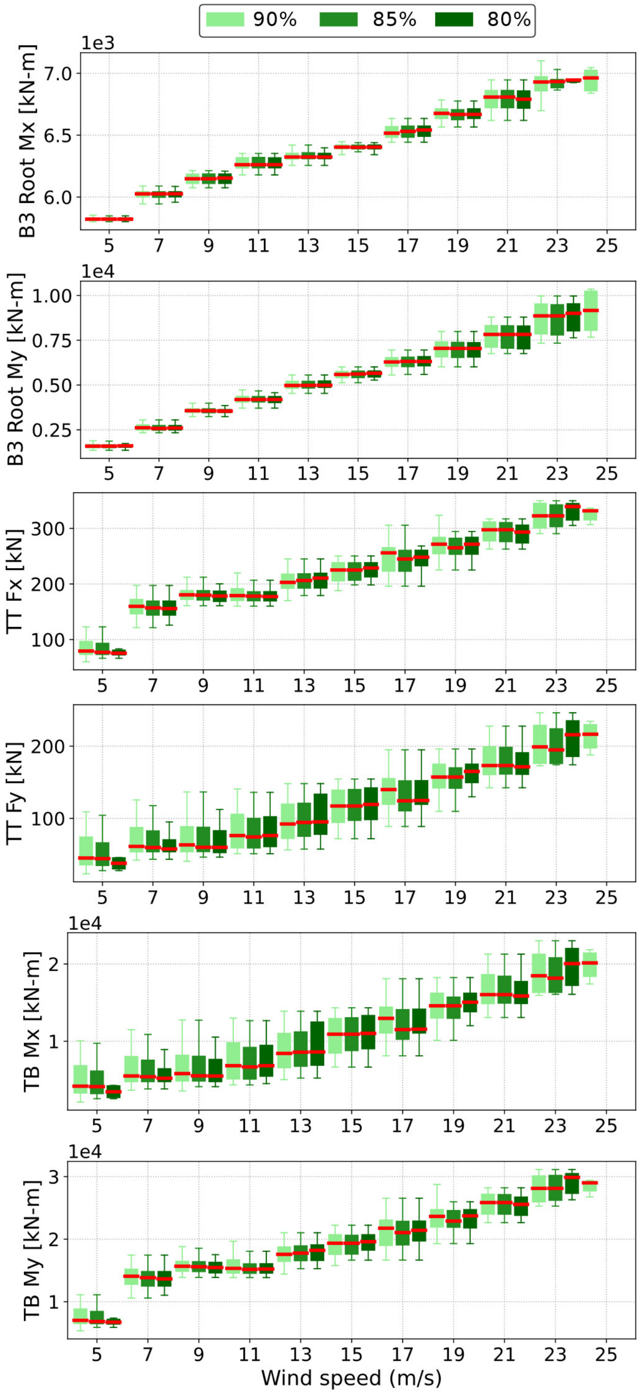

FIGURE 3: 1Hz DELs FOR THE OC4 PLATFORM GROUPED BY WIND SPEED. MEAN (RED LINE), IQR (BOX) AND MIX/MAX RANGE (WHISKERS).

When considering non-zero mean DELs, excluding conditions with high mean loads on the components may influence Lifetime DELs significantly. The impact of this can be limited if the suggested approach of gradually increasing the number of bins that are considered until the percentage variation of lifetime DELs is acceptable is followed. Lastly, we did not study how the bin size influences the results presented herein. The influence of the bin reduction method on Lifetime DELs is studied in Stewart [41], without however combining it with the probability sorting method. The combination of different bin sizes and coverages of the design space would be interesting to evaluate in more detail.

3.3 Simulation length and number of seeds

An important topic not addressed yet is simulation length. For onshore wind turbines, simulations are typically 10 minutes in length as mean wind speed can generally be considered stationary for this interval. Variations in instantaneous wind speed are introduced through a turbulence model, which relies on a turbulent spectral model such as the Kaimal model indicated in IEC 61400-3 [26]. The generated time histories are pseudo-random and depend on a user-specified input seed. It is common practice to consider multiple seeds within each DLC when performing a load calculation to ensure that all the relevant combinations of operating and inflow condition are simulated. When dealing with FOWTs, it is customary to increase the simulation length to 1-3 hours for two main reasons. Firstly, some natural frequencies of FOWTs can reach natural periods in excess of 100 s and considering 10-minute simulations may not be enough to capture this slow-varying behavior. Secondly, a sea-state can be considered constant in terms on H_S and T_P for approximately 1-3 hours [42]. The influence on fatigue and extreme loads of simulation length and number of seeds for a FOWT has been studied by Stewart [41,43] and by Kvittem [44]. In particular, Stewart found that good estimation of extreme loads requires more seeds than fatigue loads. Based on this work nine turbulent seeds were used for ultimate loads DLCs in the FLOATECH project (Tab. 1). For fatigue loads, both authors [43,44] found that total simulated time is more important than using different seeds. Moreover, as long as simulations are concatenated before post-processing fatigue loads, simulation length has little influence on results. Based on these findings, two half-hour long simulations have been considered when evaluating fatigue loads in the FLOATECH project and suggested herein.

5. CONCLUSIONS

The present study is intended to be a guideline for researchers approaching the simulation of a floating offshore wind turbines in a real environment. To this end, guidelines are provided for the following aspects:

- MET-OCEAN CONDITIONS – A review of existing study cases is provided. It is shown, however, that very few of them provide to date a good combination of resolution and completeness for the four main relevant parameters, namely wind speed (U), significant wave height (H_S), peak spectral period of the waves (T_P) and wind-wave misalignment (M_{WW}). As a possible countermeasure, a novel open-source procedure developed is proposed. This is based on high quality hindcast data obtained through the open-source database ERA-5 that are then post-processed with a Python script using the open-source tool Virocon, which is also used to compute environmental contours.

- DLCs and METRICS – Upon examination of the standards, it is apparent that a meticulous assessment (especially for fatigue loading) reproducing all the prescribed design space would result in an almost intractable problem involving several tens of thousands of simulations. Therefore, some critical DLCs are discussed, and a list of most relevant ones is proposed, which is thought to be particularly effective whenever multiple codes or simulation approaches need to be compared. To analyze the simulations, a summary of the most relevant metrics for each component is provided.
- SIMULATION COST – Even if the proposed list of DLCs is considered, a large number of simulations is necessary for the evaluation of fatigue loads due to the stochastic nature of the variables. This is often not affordable, especially if higher-order methods (e.g., those based on Computational Fluid Dynamics or other high-fidelity ones) are used. In the FLOATECH Project, two strategies to reduce the number of simulations, the *bin reduction* method and the *probability sorting* method are combined. A sensitivity analysis, based on the three study cases considered within the FLOATECH project [45], showed that while for some load sensors a lower coverage of the probability space can be considered with little to no impact on zero-mean Lifetime DELs, we recommend to consider at least 90% of the design space for most applications. During preliminary concept evaluations or other time-sensitive applications, Lifetime DELs are within 95% of the 90% coverage database when reducing coverage to 80%.

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NOMENCLATURE

Acronyms

AEP	Annual Energy Production.
DEL	Damage Equivalent Load.
COD	Co-directional
DLC	Design Load Case.
ESS	Extreme Sea State.
EWM	Extreme Wind Model
ETM	Extreme Turbulence Model
ECD	Extreme operating gust with direction change
FOWT	Floating Offshore Wind Turbine.
IEA	International Energy Agency.
IQR	Inter Quantile Range
IFORM	Inverse First Order Reliability Method
ISORM	Inverse Second Order Reliability Method
NSS	Normal Sea State.
NTM	Normal Turbulence Model
MUL	Multi-directional
PDF	Probability Density Function.
SSS	Severe Sea State.

Latin letters

H_S	Significant wave height, m.
M_{WW}	Wind-wave misalignment, deg.
T_P	Peak spectral period of the waves, s.
U	Average wind speed, m/s.

Load sensors

B1 Root Mx	Blade root edgewise moment, kNm.
B1 Root Mx	Blade root edgewise moment, kNm.
TB Mx	Tower base side-side moment, kNm.
TB Mx	Tower base side-side moment, kNm.
TT Fx	Tower top fore-aft force, kN.
TT Fy	Tower top side-side force, kN.

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