Analysis of Wind and Wave Data to Assess Maintenance Access to Offshore Wind Farms

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ABSTRACT: For offshore wind farms, maintenance operations are only possible under specific weather conditions. This has a strong impact on farm availability: given a failure, there is a chance that the maintenance crew is not able access the site safely, but has to wait for appropriate weather conditions to arise. To model the uncertainty in offshore wind farm availability growth, which is our ultimate goal, we require a probability assessment of weather windows of specific durations. This paper presents the analysis of wind and wave data collected at an offshore wind farm in the North Sea and discusses how we might extract weather window and waiting time information to support availability growth modelling. We examine the statistics of the waiting time associated with different levels of maintenance of various subassemblies of the wind turbine. Wind and wave limitations assosiated with a given maintenance operation will be critical factors in determining the level of access available to the wind farm and it is shown that slight improvement in vessel capability can result in significantly reduced waiting times and greater access.

1 INTRODUCTION

For the UK to achieve its 2020 renewable targets, offshore wind needs to increase in capacity, requiring further investment. New projects can attract capital only if the risk related to their performance is well understood, especially during early life when when relatively immature systems may show systematic reliability problems. To address this issue, we are developing a mathematical model to represent the state-of-knowledge uncertainties in availability growth projections of offshore wind farms during early operational life (Zitrou, Bedford, & Walls 2012, Zitrou, Bedford, Walls, Wilson, & Bell 2013).

The availability of a wind farm will depend on the maintenance regime employed, and for offshore wind farms, the ability to perform said maintenance depends heavily on the weather. For any given scheduled maintenance operation or failure repair, there is a chance that harsh weather conditions will render the site inaccessible or the operation unsafe to attempt or complete. In general, the ability to transfer personnel to a turbine is limited by wave conditions and the operations which can then be performed safely depend on the wind conditions. Further constraints limit the use of jack-up or field support vessels for craning operations involving large and/or heavy components.

Our wind farm availability growth model captures the effect of weather on downtime by describing the delay of maintenance given a certain type of failure. In particular, the time it takes to restore a failure is described in terms of a logistic time (i.e. time it takes to collect equipment), a waiting time (i.e. amount of time the crew has to wait until weather allows to undertake maintenance), a travelling time and a repair time.

This article presents the analysis of wind and wave data collected at an offshore wind farm in the North Sea with a view to extracting information on weather window and waiting times. Similar analysis can be performed on larger data sets to support the quantification of the wind farm availability growth model.

Note that we are only concerned with restrictions on access imposed by wind and wave conditions for the purposes of our higher level modelling of availability growth in early operational life. Hence we do not need to consider other aspects affecting the ability to perform maintenance such as the availability of spare parts, vessels and personnel that can be relevant in other analysis such as models designed to inform descision making. Two such models are compared in Rademakers et al. 2003.

This paper is organised as follows. In Section 2, definitions of notation and terminology used throughout this paper are given. In Section 3 the method developed to extract the weather windows and estimate waiting times is explained. The analysis of the wind and wave data and our findings of weather window analysis for maintenance operations performed by different types of vessel are given in Section 4. Some conclusions and suggestions for further work are drawn in Section 5.

2 NOTATION AND TERMINOLOGY

Weather Window A period of time during which if a given maintenance operation is started, it can be completed.

Waiting Time The amount of time an operation is delayed due to constraints on sea state and wind speed. Note that the availability of spare parts, personnel, vessels or other weather constraints are not considered.

$\boldsymbol{H_s}$ *Significant Wave Height.* The mean height of the highest third of all waves in a given time period. This is a standard measure of sea state. (Faltinsen 1990)

CTV *Crew Transfer Vessel.* Most commonly catamarans though monohull and SWATH (small waterplane area win hull) varieties are also used. These vessels have limited range and cargo/crew capacity. Operational limits have a large range of between 1m and 2.5m H_s depending on vessel type and size.

FSV *Field Support Vessel.* Large monohull vessels with large crew and cargo capacity, capable of remaining at sea for 5–7 weeks (Tavner 2012) to take advantage of short weather windows. Equipped with a crane though not capable of removing large components such as blades from a turbine. Used for many years in the oil and gas industry creating a large base of experience though competing with this industry could increase the already volatile day-rates.

Jack-up *Mobile Jack-up Installation.* Huge vessel equipped with legs which can be lowered to the sea bed and raise the main hull above the water providing a stable platform for heavy lifts. Equipped with a large crane capable of removing/installing large components such as blades, generators and gearboxes. Can remain at sea for long periods to take advantage of short weather windows, facilities on-board allow for long, stable shift patterns.

3 DATA AND METHODS

3.1 *Weather Data*

Wind and wave data from the FINO1 research platform is used for our analysis to measure the frequency and duration of weather windows and calculate the probability distributions of waiting times for a variety of maintenance operations. The FINO data is in the form of hourly mean wind speeds and hourly significant wave heights collected over a period of six years.

FINO1 is situated in the North Sea, approximately 45km to the north of Borkum, Germany, where the water depth is approximately 30m. The exact site coordinates are as follows: N54° 0.86’ E6° 35.26’. The analysed data was recorded between 1/1/2004 and 1/10/2010 comprising 59182 time points.

The location of FINO1 is comparable to many of the UK Round 3 sites, particularly Hornsea and Norfolk Bank which cover areas between 30km and 190km from shore with water depths between 30m and 40m . The largest Round 3 site, Dogger Bank, is between 125km and 290km from shore with water depths ranging from 18m to 63m. Other Round 3 sites are closer to shore and have significantly different geography from the FINO1 station being either in the English Channel or Irish Sea for example.

3.2 *Subdivision of the Wind Turbine System*

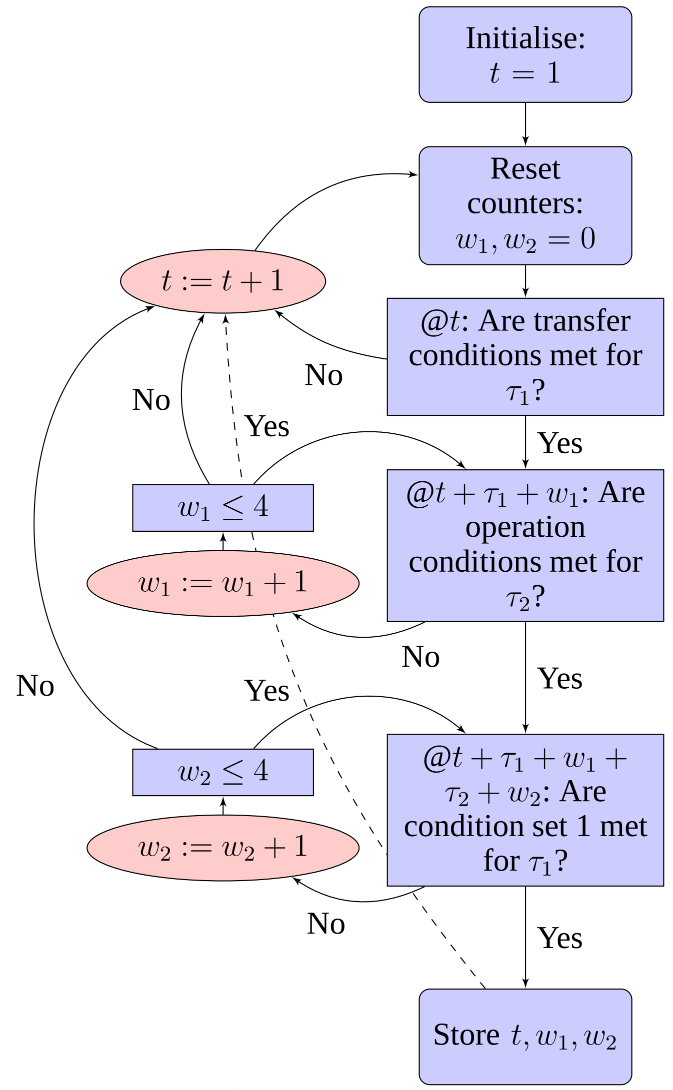
The wind turbine is divided into 7 modules consisting of a total of 20 subassemblies, see Table 1, only the wind turbine is considered — sub-sea cables, offshore substations and so on are not included.

3.3 *Maintenance Classes*

Three possible maintenance classifications, *major*, *moderate* and *minor*, are considered for each subassembly and vessel and weather constraints are applied accordingly. This system of classification is based loosely on that found in Rademakers and Braam 2002 and Faulstich et al. 2011.

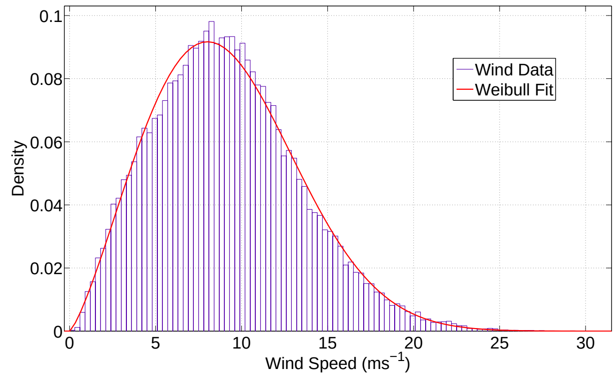
Each maintenance class for each subassembly is assigned one of three vessel types, Jack-up, FSV or CTV, and appropriate time and weather constraints depending on the nature of the operation, Table 2.

Wind constraints depend on the need for external cranes or access to the turbine roof or hub, for example, and wave constraints are largely vessel depen-

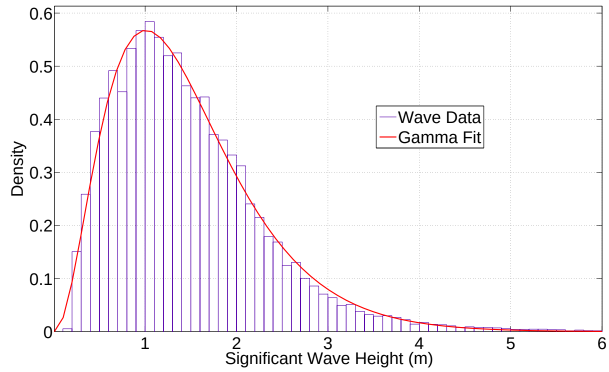


t	Time Index
τ_1	Transfer/Jacking Duration
τ_2	Operation Duration
w_1, w_2	Delay

Figure 1: Flow chart of window counting procedure implemented in MATLAB.



(a) Probability distribution and Weibull fit for hourly mean wind speeds.



(b) Probability distribution and gamma distribution fit for hourly mean significant wave height.

Figure 2: Probability distributions and PDF fits for wind and wave data.

dent, transferring from CTV to the turbine for example. Wind constraints not relating to the use of cranes mounted on ships are assumed to be the same as the onshore case as in McMillan and Ault 2007. Wave constraints are informed by Tavner 2012.

3.4 *Computing the Waiting Time Distributions*

The availability growth model is implemented as a simulation model in MATLAB (Zitrou et al. 2013). Within the general mathematical framework for the availability growth model, the reliability of subassemblies is described in terms of non-decreasing rates. Restoration behaviours are determined in terms of aspects such as ease of repair, ease of access to the offshore site, availability of maintenance resources like vessels etc. The waiting time given the failure of a particular subassembly is represented as a random variable. For the purposes of Monte Carlo simulation, one needs to determine a parametric model for the uncertainty on the waiting time.

Hence we firstly require to obtain the empirical distribution of waiting times for the different subassemblies and maintenance classes from our data and then we need to fit a parametric probability distribution to the empirical data.

The weather data is searched by a MATLAB program designed to find and count weather windows given a set of constraints and record their position in the data set. From these results the distribution of waiting times is calculated. Seasonal information is easily extracted, each season is considered to be 3 months long, winter being from the beginning of November to the end of January and so on.

The search algorithm is illustrated in Figure 1. Each maintenance operation, regardless of vessel type, consists of three phases — two transfer phases either side of the main operation phase. The weather constraints can be substantially different for the transfer and operations phases. The model allows for a delay between phases of up to 4 hours to maintain a degree of flexibility.

Module	#	Subassembly	Description
Power Module	1	Generator	The generator converts the mechanical energy produced as the rotor rotates into electrical energy.
	2	Frequency Converter	(For variable speed WTs) The converter turns variable speed power into fixed frequency and fixed voltage power.
	3	Transformer	The transformer converts the electricity to the right voltage for the distribution system (from WT voltage to medium voltage line).
	4	Electrical Power Systems (Other)	Includes components such as switchgears and power feeder cables.
Drive Train	5	Gearbox	The gearbox adapts rotor to generator speed.
	6	Main Shaft	Including bearings. The (rotor) shaft is used to transmit power. It also absorbs (by the two main bearings in the shaft) the enormous forces generated by the weight of the rotor. There may be a low and a high speed shaft.
	7	Mechanical Brake	The mechanical brake holds the rotor stationary when the turbine is not operating.
Rotor	8	Pitch System	Pitching hubs allow the angle of each individual blade to be adjusted electrically to control the rotor speed and power output. All the drive components and control units are integrated in the hub. The slip ring connects the pitch system with the control system.
	9	Rotor Blades	The hub connects the blades to the low-speed (main) shaft. This assembly includes the blades and blade bearings, the hub cover and the hub.
Control & Communication	10	Top Box	The controller ensures the safe operation of WT (e.g. avoid over-speeding). This category includes other components such as sensors and the meteorological station.
	11	Bottom Box	
	12	Communication System	
	13	Sensors and Met Station	
Nacelle Module	14	Nacelle	The nacelle encloses the components of the mechanical drive train and of the electric generator. This assembly includes the nacelle structure and bedplate. The bedplate transfers rotor forces to the tower.
	15	Yaw System	Yaw drives position the wind turbine in relation to the wind automatically. These usually use planetary gears with electric motors and brakes. Wind directions is determined by using an anemometer at the top of the nacelle.
Structural Module	16	Tower	Steel structure fixed to the foundations and supporting the nacelle.
	17	Foundations (inc. transition piece)	Steel or concrete structure fixing the tower to the seabed.
Auxiliary Systems	18	Safety Systems	
	19	Hydraulic System	The hydraulic system mainly operates the braking systems, though sometimes also pitch.
	20	Cooling System	Energy losses accrue during operation, mostly in the form of heat, making it necessary to cool using air, water, oil/water or oil/air heat exchangers.

Table 1: Division of wind turbine system into modules and subassemblies.

Maintenance Class	Repair Duration	Logistics	Vessel Requirement	Example
Minor	Less than 1 day	Small Crew	CTV	Replacement of carbon brushes.
Moderate	1–2 Days	Medium Crew	FSV	Replacement of yaw motor.
Major	More than 2 days	Large Crew, External Crane	Jack-up	Replacement of hub.

Table 2: General description of the three maintenance classes.

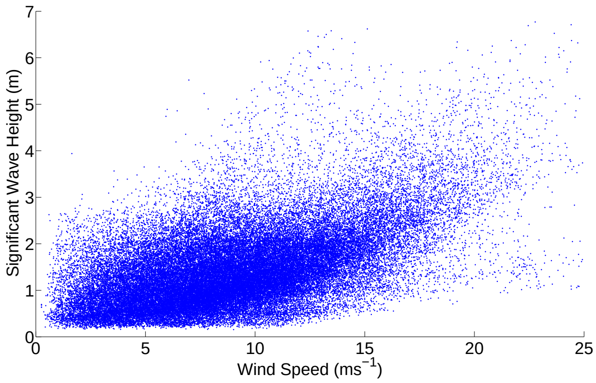


Figure 3: Scatter diagram of wind speed and significant wave height.

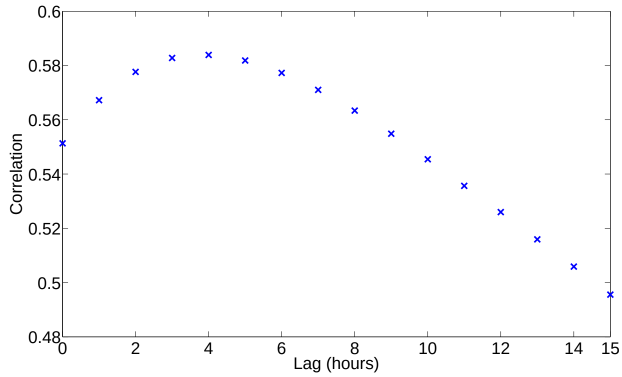


Figure 4: Correlation between wind speed and lagged significant save height.

4 ANALYSIS AND FINDINGS

4.1 *Preliminary Analysis of Wind and Wave Data*

Figures 2(a) and 2(b) show the distribution of hourly mean wind speeds and significant wave heights, respectively. Both empirical distributions are right-skewed. The mean wind speed is 9.1ms^{-1}, and the median wind speed is 8.8ms^{-1}. The mean significant wave height is 1.5m and the median significant wave height is 1.3m. Although not required for our purposes, it is common to fit parametric distributions to such weather data. We find that a Weibull distribution, with maximum likelihood estimated (MLE) shape and scale parameters of 2.29 and 10.3 respectively, fits the mean hourly wind speed data and a Gamma distribution fits the wave data with MLE shape and scale parameters of 3.21 and 0.455 respectively.

A scatter diagram of the wind and wave data is shown in Figure 3. There is a clear positive relationship but also considerable variation, especially at higher wind speeds. The presence of such patterns of variation make it important to consider both wind and wave conditions for assessment of access to offshore structures.

The estimated Pearson correlation function between wind speed and significant wave height computed at different time lags is plotted in Figure 4. The pattern emerging illustrates the lag of the sea state behind wind speed. This can be interpreted as an anti-clockwise motion around the scatter diagram, Figure 3.

4.2 *Probability Distributions of Waiting Times*

From the data we can obtain information about when delays occur and for what duration so that the empirical waiting time distribution can be established. Figure 5 shows the cumulative distribution function of the waiting time based on analysis of all our data (labelled empirical) and by season (labelled summer through winter) for the case where minor maintenance is to be conducted on a generator.

As mentioned in Section 3.4, we require a parametric form of the conditional waiting time distribution to support simulation of the availability growth model. We find that the Gamma distribution fits our empirical waiting time distributions well. Figure 5 also shows this fitted conditional Gamma distribution of waiting times (labelled Gamma fit). Parameters for the each fitted Gamma distribution were determined by maximum likelihood estimation.

4.3 *Findings for Selected Subassemblies and Maintenance Classes*

It is impractical to show all our results for all subassembly and maintenance class combinations. Hence we select a few interesting findings that might have a high impact on availability due to, for example, notable sensitivity to operational constraints, or because they relate to subassemblies that have greater susceptibility to failure.

As intuition might suggest, we found that the waiting time distributions were all right skewed and they shifted to the right as we moved from minor through to major maintenance classes. This is not unexpected given that longer weather windows and more strin-

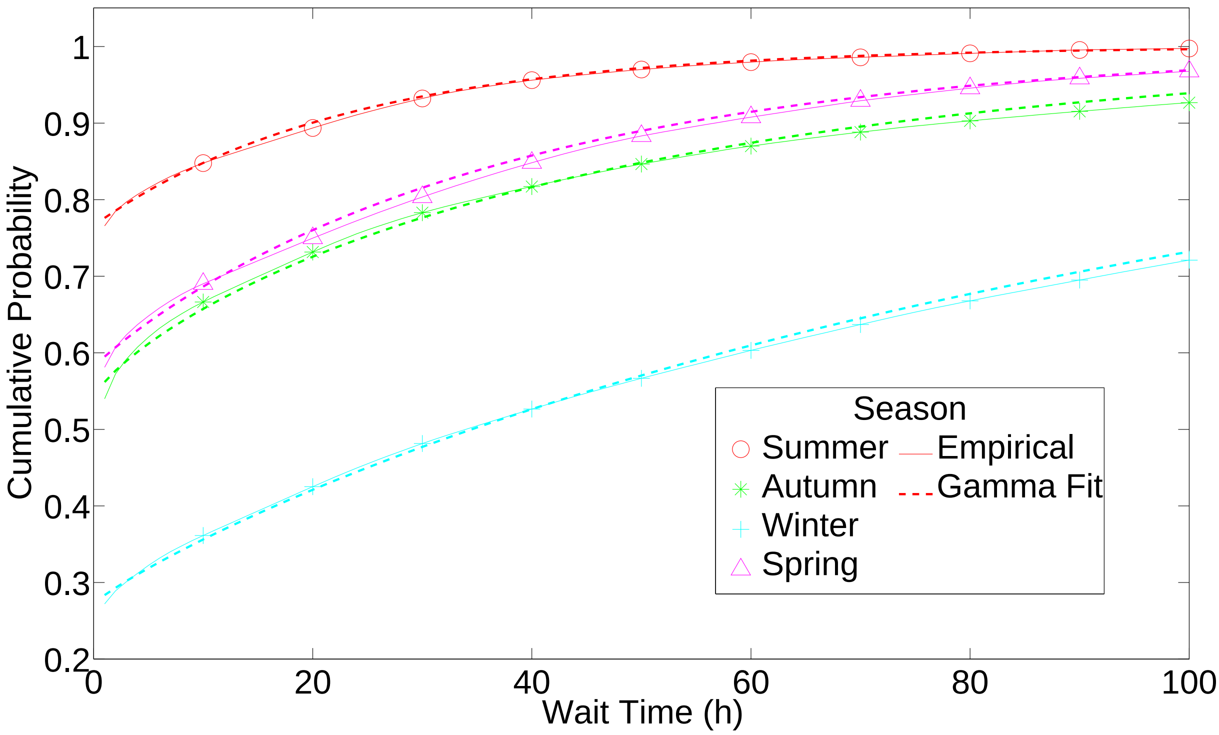


Figure 5: Empirical waiting time distributions (solid lines) and their parametric fits (dashed lines) for a minor maintenance operation on the generator in summer (○), autumn (∗), winter (+) and spring (△).

gent weather constraints are required for access to the offshore farm for more major maintenance.

4.3.1 *Major Maintenance of Generator, Gearbox and Rotor*

Here we examine the major maintenance of the generator, gearbox and rotor. This maintenance class requires the use of a jack-up vessel to complete a 48 hour operation, typically to switch-out the subassembly in question for a working unit. The damaged unit can then be repaired at a later date in order to reduce down time. Empirical distributions of the waiting times for the complete data set and individual seasons are shown in Figure 6 for craning wind limits from 6ms^{-1} to 10ms^{-1}.

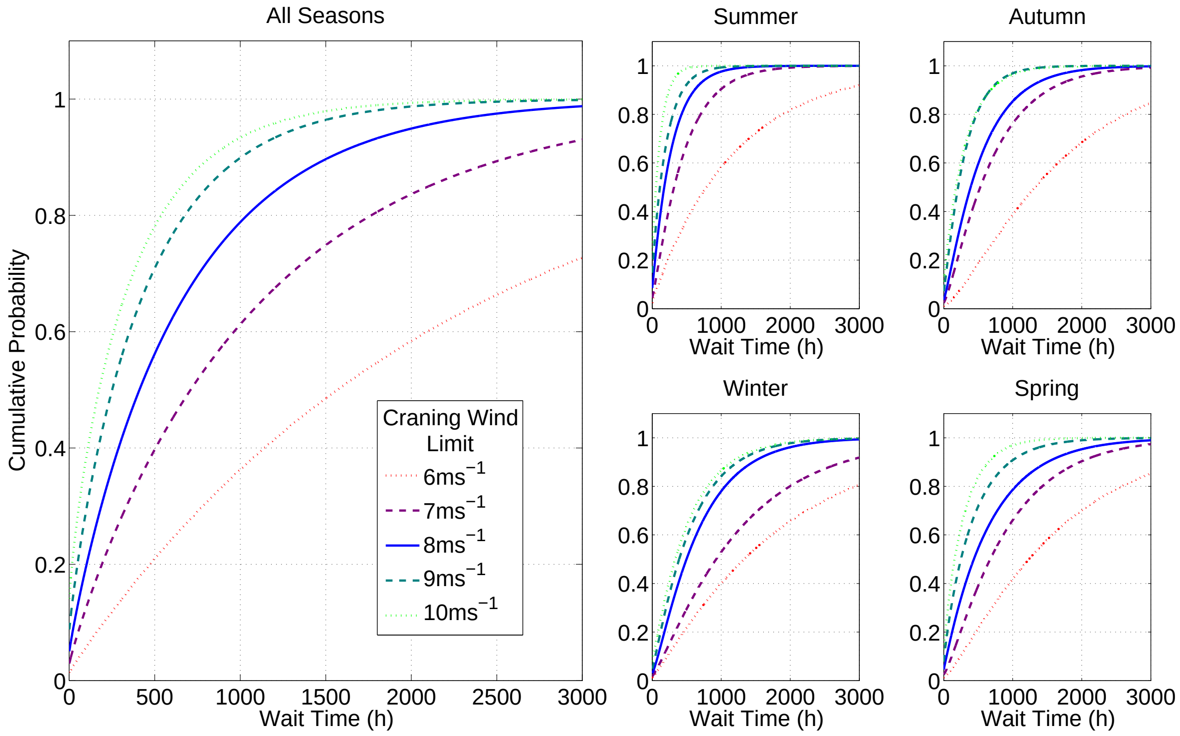
The patterns in the figure show that as the wind limits placed on craning are reduced, there is a higher chance that the waiting duration will be longer. For example, if the limit changes from 6 to 10 ms^{-1}, then the chance of having to wait longer than two weeks for a weather window to open rises from 35% to 85%. These sorts of patterns make intuitive sense from the engineering perspective. A jack-up vessel may take 4 hours to lower its legs and raise its hull above the water, a short process with modest weather constraints, but once jacked and stable platform for craning is created, the sea state has little impact on the operation. The wind, however, severely limits the use of the crane, especially given the length of time required to perform heavy lifts. Onshore, the wind limit for craning a large component is 7ms^{-1} (McMillan and Ault 2007) whereas offshore values have been quoted from 6ms^{-1} to 10ms^{-1}.

The craning wind limit has a effect on the waiting times in all seasons. For example, consider the patterns in the summer and winter seasons. Typically the distributions shift to the right as we change from a summer weather pattern to a winter one. In addition, the shape of the distribution changes as there is, on average, longer waiting times and greater variation in the winter season. Again such findings are not unexpected. Intuitively they make sense and it has already been reported by others, including Tavner 2012 and Dinwoodie and McMillan 2013, that this combination of long down time and the need for expensive vessels make this and similar maintenance classes a key cost driver over the life time of offshore wind farms.

4.3.2 *Minor Maintenance of Pitch System*

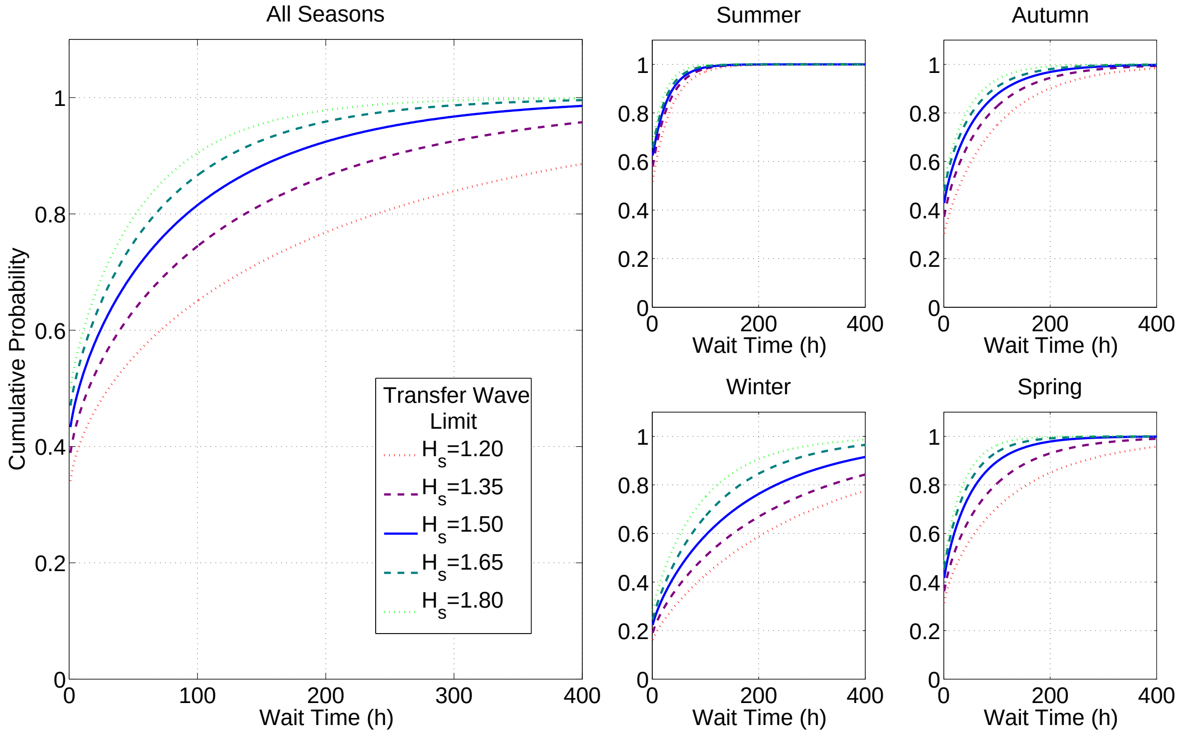
The pitch system is one that historically has a high rate of failure and impact on down time classed as requiring minor maintenance (Wilkinson and Hendriks 2011). It should be noted that many other subassemblies have similar minor maintenance requirements, but for illustration we present only the pitch system. The required maintenance of the pitch system can be carried out in a single day by a small crew with little heavy equipment and no need for an external crane. The critical constraint on this type of operation is the transfer wave limit — the maximum significant wave height at which it is safe to transfer personnel from the CTV to the turbine, typically around 1.5m.

The empirical distributions of waiting time for the complete data set and individual seasons are shown in



Jacking Wave Limit	Jacking Wind Limit	Jacking Time	Operation Wave Limit	Operation Wind Limit	Operation Time
1.6m	15ms^{-1}	4h	5m	6–10ms^{-1}	48h

Figure 6: Sensitivity of conditional waiting time to craning wind limit for operations corresponding to major maintenance of generator, gearbox or blades requiring a jack-up vessel.



Transfer Wave Limit	Transfer Wind Limit	Transfer Time	Operation Wave Limit	Operation Wind Limit	Operation Time
1.2–1.8m	20ms^{-1}	1h	4m	12ms^{-1}	12h

Figure 7: Sensitivity of conditional waiting time to transfer wave limit for minor maintenance of pitch system requiring a CTV.

Figure 7 for crew transfer wave limits from 1.2m to 1.8m significant wave height.

The patterns emerging in the data show that the winter waiting time is most affected by the transfer wave limit with very little difference in the summer months. For example, in summer we are almost guaranteed that we shall have to wait no more than 4 days, whereas in spring and autumn our maximum waiting time will be around 10 to 15 days. In winter, there is greater sensitivity to the transfer wave limit with the maximum observed waiting time ranging from 2 weeks at H_s=1.8m to 6 weeks at H_s=1.2m. Thus there is an argument for investing in sturdier vessels which can transfer personnel to turbines in rougher seas to boost access, and therefore availability, during the winter.

5 CONCLUSIONS AND FURTHER WORK

Our goal has been to determine the waiting time distributions for combinations of offshore wind farm subassemblies under different maintenance scenarios as an input to an availability growth model (Zitrou et al. 2012, Zitrou et al. 2013). We require both the method for generating these waiting time distributions from typical empirical data collected at wind farms and the results in terms of the parametric models that describe behaviour of the waiting time distributions across the matrix of subassembly and maintenance class combinations.

We have demonstrated the applicability of the method and shown a selection of findings using data collected from one offshore wind farm. Of course, the insights gained are limited to the one farm that we have studied. However the general method can be applied more widely as data is made available to develop a more general class of waiting time distribution characteristics under different scenarios.

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