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WEATHER DOWN TIME ANALYSIS FOR OFFSHORE WIND FARM INSTALLATIONS

by

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KEY WORDS:

Discrete Event Simulation, offshore wind farm, weather down time, time window, probability

MOTS-CLES:

Simulation à Événements Discrets, champ d'éoliennes offshore, retards induits par les conditions météorologiques, fenêtre de temps, probabilité

1 INTRODUCTION

The offshore wind energy has been progressing in the last 10 years. The annual offshore wind installation increases from 89.97 MW in 2004 to 1483.3 MW in 2014 [1]. According to the European Wind Energy Association, 20 % of the energy mix should come from renewable energy by 2020 [EWEA, 2007]. The European Wind Energy Association expects that by 2020 offshore wind power will account for 4 to 4.2 % of Europe's energy demand with an installed capacity of 40 GW, [2,3].Even though there exists a large amount of wind energy on European waters, it has several problems, such as high cost of transport and installation. The transport and installation of offshore wind turbines is highly dependent on weather condition at sea. Any disturbance along the logistics chain could result in a significant delay in the project completion. It has been discovered [4] that disturbances due to weather restrictions during the process of installing the turbine components at sea can lead to a significant increment of logistics costs.

Green and Vasilakos [5] noted that most of the costs associated with offshore wind energy development are still much higher compared to onshore counterparts. The need for utilising expensive transportation resources gives rise to substantial difference between onshore and offshore operations. The transport and installation cost of an offshore wind farm could range between 5 % and 30 % of the total cost of the investment [6], [7], [8], [9], [10]. Effective planning of the transport and installations procedures could help minimise the entire cost of the project completion. The purpose of this paper is to carry out the weather down time analysis for the transport and installation of the offshore wind farm applying the Discrete Event Simulation (DES).

2 METHODOLOGY

The model has been developed using the Discrete Event Simulation and takes into account the activities within the transport and installation phase. There are mainly three assembly strategies currently used in the offshore wind industry:

1. Rotor Star (RS) – Three blades and hub are pre-assembled to form a rotor in the staging area. Then, the rotor is transported to offshore site.
2. Single Blade (SB) – All the wind turbine parts are transported to the offshore site and installed one by one.
3. Bunny Ears (BE) – Two blades are pre-assembled forming a bunny ears in the staging area. Then, the last blade is installed independently at the offshore site.

In general the offshore wind farm comprises a number of phases such as the pilling, foundation, turbine component transport and installation. Different phases require different types of resources and it could be carried out by different companies. In this paper the weather down time analysis is carried out for the turbine component transport and installations phase. The development of the model and the input parameters has been explained in detail hereafter.

2.1 Discrete Event Simulation (DES)

Discrete Event Simulation (DES) only takes into consideration points in time (events). Such events may, for example, be an element entering a station or leaving it, or moving on to another machine. Any movement in between is of little interest for the simulation itself. What is important is that the entrance and the exit events are assessed correctly. When the element enters a material flow object, the software calculates the time until it exits that object. [11] Pointed out that simulation helps to quantify the cost of O&M and also indicated that larger wind turbines can lead to lower O&M costs.

2.2 Model Description

The activities within the logistics chain have been modelled by Discrete Event Simulation. The number of lifts at the offshore site depends on the installation strategy and for this study the single blade installation strategy has been implemented. This installation strategy is defined in such a way that all the turbine components will be transported to the offshore site without any pre-assembly operation and the parts will be installed one by one. Some activities are not weather dependent and do not require computation of monthly working percentages.

1. **Mooring:** This is the first activity where the vessel will be secured in order to load the turbine components. This activity is not weather dependent.
2. **Loading:** The loading operation for each turbine component is dependent on the weather conditions and it starts with tower loading, then nacelles loading and finally blades. It has both working and down time due to the weather conditions.
3. **Unmooring:** Once all the turbine components are loaded and the ship is ready to sail, the mooring system will be released. This activity is not weather dependent.
4. **Transportation:** There should be good weather conditions during the sailing time and the longer the distance the higher the weather down time. In order to avoid a long duration of the weather window down time for the transport phase, it has been split into two phases where a transition point will be considered between the port and the offshore site.
5. **Positioning and set up:** At the offshore site, the vessel should first be properly positioned so as to carry out the installation activities and additional set up activities are also required. It is weather dependent and the wave height is the dominant weather restriction factor for this section.
6. **Installation:** As already mentioned in the previous section, the parts will be installed one by one based on the availability of good weather. The installation process is highly affected by the weather conditions and the wind speed is the dominant factor. The installation time is divided into two namely set up (preparation) time and installation time.
7. **Jack Lowering:** After completing the installation of one complete Offshore Wind turbine, the next step is jacking down. It is also weather dependent (wave height).
8. **Transportation:** This is the trip back to the port in order to load the remaining turbine components and similar procedure will be followed as the one to the offshore site mentioned in terms of weather time window. If all the turbines are installed, this will be the last activity of the discrete event simulation model.

2.3 Weather Conditions

The most important input parameter for the offshore transport and installation activities is weather data at a specific site. The weather time series data have been obtained from a meteorological station for the period of 1995-2008 for wind speed and wave height. Both historical weather data and a probabilistic approach may be used to analyse the project lead time of completing the installation of the offshore wind turbines. Weather predictions and numerical weather forecasts can be calculated with different models. However, the reliable weather predictions are mostly provided for a period of approximately a maximum of 14 days [12]. This is obviously not appropriated for a long-term scheduling. Muhabie et al. [13] compared the installation of offshore wind farms, based on Discrete Event Simulation, using both historical weather time series and probabilistic approaches and it was found out that both approaches showed a good agreement. In this study a probabilistic approach has been implemented where the monthly probability of working and non-working is computed based on the weather restrictions and time window criteria for a specific activity.

1. Workability: refers to the condition above in which an operation cannot be carried out anymore (could be wind speed or wave height or both).
2. Time window: refers to good weather conditions in order to complete an operation and is simply the range of workability.

It is known that the wind measurement is taken at a specific height and there should be a way to find the wind speed at a working condition at the offshore site. The wind profile power law relationship, presented in equation 1, is used to estimate the wind speed u at height z, where u_r is the known wind speed at a reference height z_r , [14]. The exponent α is an empirically derived coefficient that varies dependent on the stability of the atmosphere. The shear exponent α varies depending on atmospheric conditions, temperature, pressure, humidity, time of the day and nature of terrain [15]. The shear component can typically be assumed to be equal to 0.1 in offshore environment [16, 17].

$$u = u_r \left(\frac{z}{z_r}\right)^{\alpha} \qquad (1)$$

It is assumed that the percentage of monthly workability assumes normal distribution over time. In order to generate the normal distribution, the mean and the standard deviation of the percentage workability computed, have been taken in to account. The weather condition at sea changes randomly from time to time and different scenarios have to be taken in to account. In this paper three

Scenario	January	February	March	April	May	June	July
Q80	46	54	71	78	81	83	84
Q50	61	67	78	86	87	89	90
Q20	76	80	86	94	92	96	95
Scenario	**August**	**September**	**October**	**November**	**December**	**Average**	
Q80	85	77	65	63	55	70	
Q50	90	84	75	72	68	79	
Q20	95	91	85	80	82	88	

Table 1: Monthly workability percentages (Best, Average and Worst) over the year

different weather scenarios (Best, Average and Worst) have been considered and computed applying the cumulative distribution function (CDF) and its inverse distribution function (Quantile function). The cumulative distribution function of the workability (for each month) may be expressed by equation 2.

Where

$$F(x) = P(X <= x) \quad (2)$$

F(x) – the cumulative distribution function
P(x) – the monthly working probability for a specific year

The quantile function (for example Q80) can be computed by finding the value of x such that *F(x)* =0.2.

1. Best weather condition (Q20): Under this assumption the weather is assumed to be at its best condition in order to perform an operation and can be computed using the complementary cumulative probability function.
2. Average weather condition (Q50): this simply refers to the mean value of the monthly working percentage and it also represents the mean of the normal distribution.
3. Worst weather condition (Q80): Under this assumption the weather is assumed to be at its worst condition in order to perform an operation and can be computed using the complementary cumulative probability function.

Table 1 presents the monthly workability percentages for three different weather scenarios (Best, Average and Worst), where the time window is considered to be 1 hour and the limiting factor (wind speed) is 15 m/s.

3 RESULTS AND DISCUSSION

This section presents the results. Since the monthly working percentage is probabilistic, we need to find the number of simulation runs for which convergence will be reached. For instance, a method will be triggered and based on the weather restrictions, time window and associated probability, it gives a value of 0 or 1 which is considered as a deciding factor whether to proceed to the next activity or to wait until good weather exists. The loop iterates until the result is 1 which gives a green light to carry out a certain activity (sailing, installing, loading, etc.). The time elapsed until the iteration gives a result of 1 is considered as a waiting time. Changing the random stream number will change the sequence of the binary values and it will result in having different waiting times until it reaches a green light, thereby making the output lead time stochastic (Fig. 1). Fig. 2 presents a convergence test for a specific start date of the project in July and it is clear from Fig. 2 that the mean values tend to converge roughly after 280 iterations.

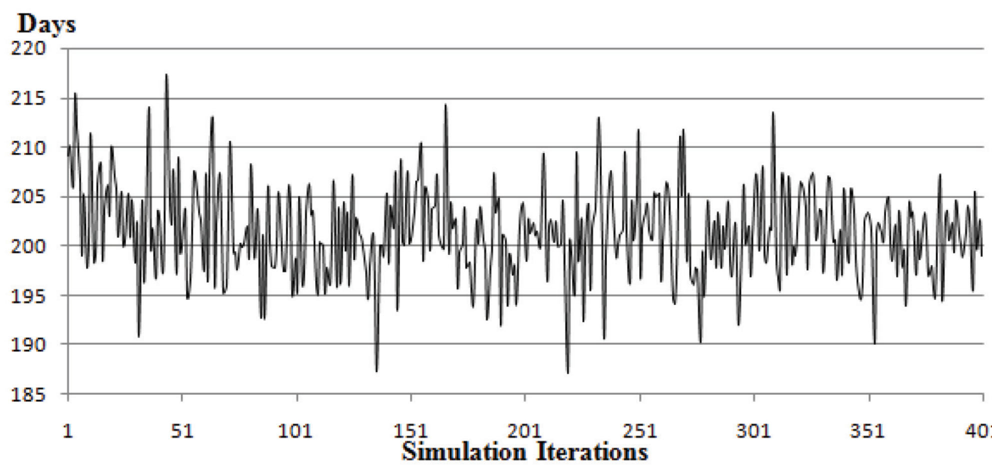

Fig. 1: The lead time for each simulation run installing 72 OWTs

Activity	Duration(Hr)	Weather Window(Hr)	Limiting Factor	Limit	Category
Tower Loading	1:49	3:00	Wind speed	12m/s	Lifting
Transport	14:16	18:00	Wave height	2,25m	Sailing
Positioning Jacking	5:53	6:00	Wave height	1,5m	Jacking
Cycle related activities	1:27				Cycle related activities

Table 2: Sample input parameters showing activity, time window and weather restrictions

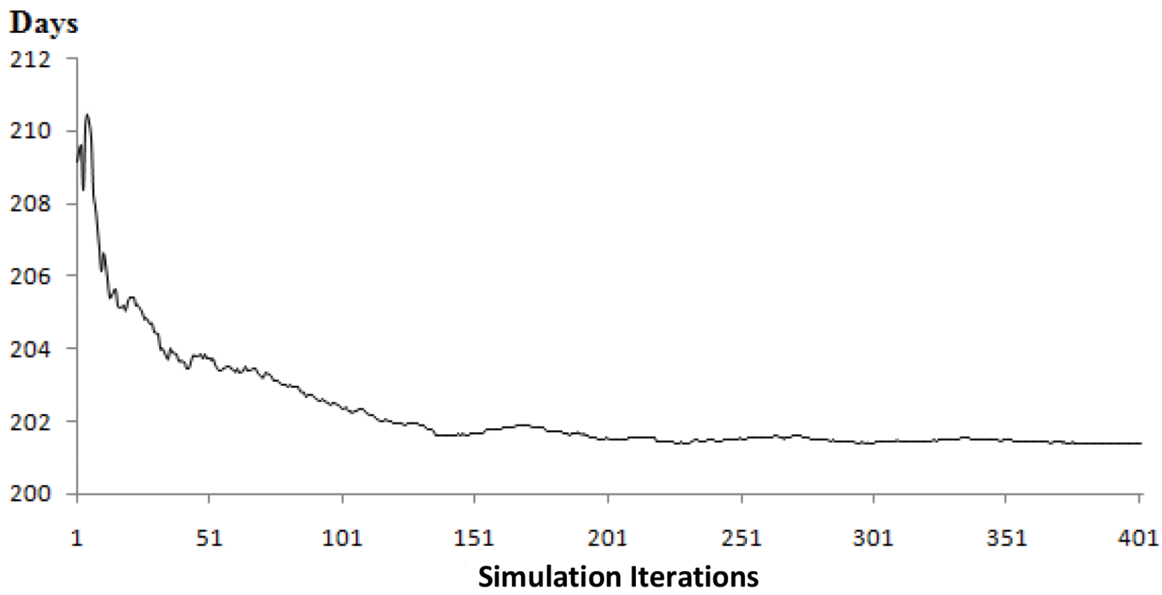

Fig. 2: The convergence test showing the minimum number of simulation runs required for installing 72 OWTs

It should be noted that the start date of the project is considered to be the month of July for all the analyses presented in this paper and 400 simulation runs have been considered for each start date of the project in order to quantify the weather down time along the logistic chains. An activity time has been allocated for each operation where 15 % is incorporated as a safety factor representing any delay due to personal inefficiency or machine breakdown and non-weather-related loss. If the time required to complete a certain operation is 4 hours, 4 + 4*0.15= 4.6 hours has been considered in the analysis. For the weather dependent activities, the time window required for computing the workability percentage is higher than the time required to complete the operation. This is very important in risk reduction for major projects and temporary phase marine operations. Some examples have been presented in Table 2 showing the activity time, weather window and weather restriction values.

All the activities considered in this study have been divided into four categories depending on the nature of the activity.

1. Lifting: refers to the activities like loading and installing the parts of the Offshore wind turbine.
2. Sailing: refers to the transportation phase of the project.
3. Jacking: refers to the activities related to positioning, jacking up and down.
4. Cycle-related activities: refers to the activities carried out per turbine at the offshore site before installing tower and after installing the last blade.

In order to illustrate the simulation model developed, a case study has been performed and presented. The weather down analysis has been carried out for transport and installation of 72 turbines in the North Sea considering the three different weather scenarios (Best, Average and Worst). The project lead time is defined as the time elapsed from the start of the project until the completion of installing 72 turbines at the offshore site. The vessel capacity is assumed in this study as 3 sets of turbine components and there exist 24 trips so as to complete the entire installation operations. Fig. 3 presents the lead time for three different weather scenarios (Q20, Q50 and Q80) which are 223.64, 270.93 and 337.56 days respectively. It also shows the weather down time for three different weather scenarios (Q20, Q50 and Q80), which are 75.9, 123.2 and 189.8 days, respectively. The analysis indicated that the lead time has increased by 21.1 % and 50.9 % when Q20 is compared to Q50 and Q80, respectively. The lead time has also increased by 24.6 % when the weather scenario changes from average (Q50) to Worst (Q80) and this type of analysis helps the planner in providing an insight how the weather at sea highly affects the project lead time.

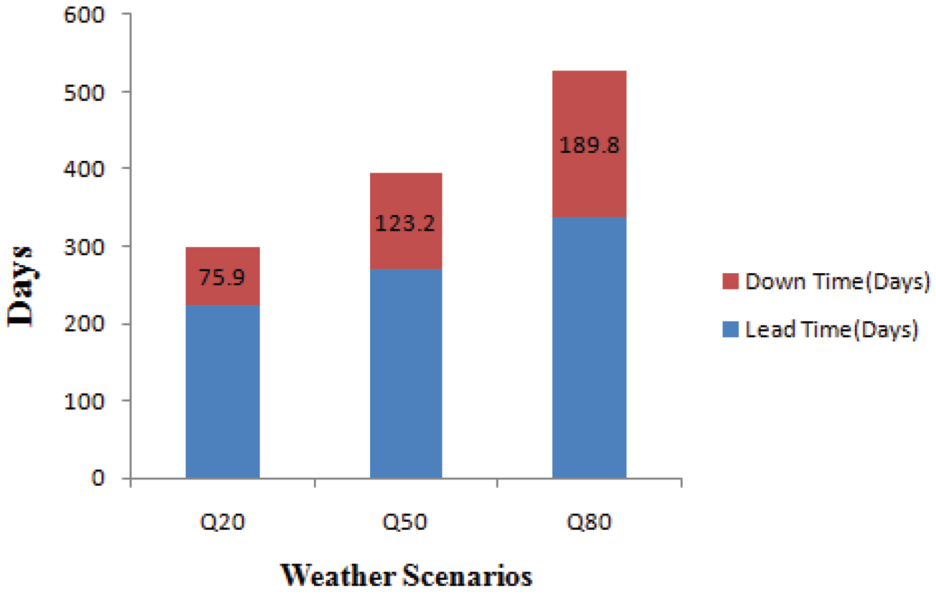

Fig. 3: The lead time and weather down time for installing 72 OWTs considering three (Best, Average and Worst)

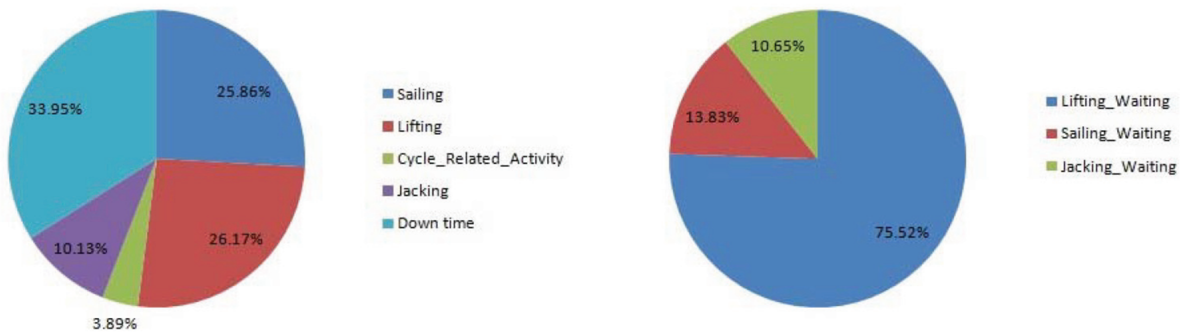

Fig. 4: The percentage of the time spent for different activities under the categories of sailing, lifting, cycle-related activities, jacking and down time (Q20)

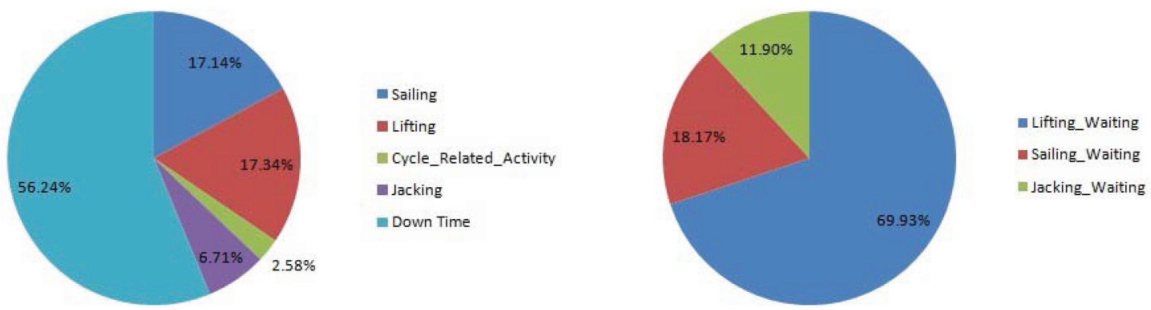

Fig. 5: The percentage of the time spent for different activities under the categories of sailing, lifting, cycle-related activities, jacking and down time (Q80)

Further analysis has also been carried out in order to investigate the weather down time and its cause during the transport and installation operations. Fig. 4 depicts the percentage of the time spent for different activities (Q20) under the categories of sailing, lifting, cycle related activities, jacking and down time. Sailing and lifting combined represents 52.04 % of the entire project lead time and the weather down time represents 33.95 % of the lead time. Looking at the causes of the down time, 75.52 % of weather down time is caused by the lifting operation in which the wind speed is the dominant factor.

Fig. 5 depicts the percentage of the time spent for different activities (Q80) under the categories of sailing, lifting, cycle-related activities, jacking and down time. Sailing and lifting combined represents 34.48 % of the entire project lead time and the weather down time represents 56.24 % of the lead time. Looking at the causes of the down time, 69.93 % of weather down time is caused by the lifting operation in which the wind speed is the dominant factor. When we consider the down time percentage for the worst-case scenario (Q80), the down time (56.24 % of 337.5 days) has increased by 1.5 folds compared to the best-case scenario (Q20), which is 33.95 % of 223.64 days.

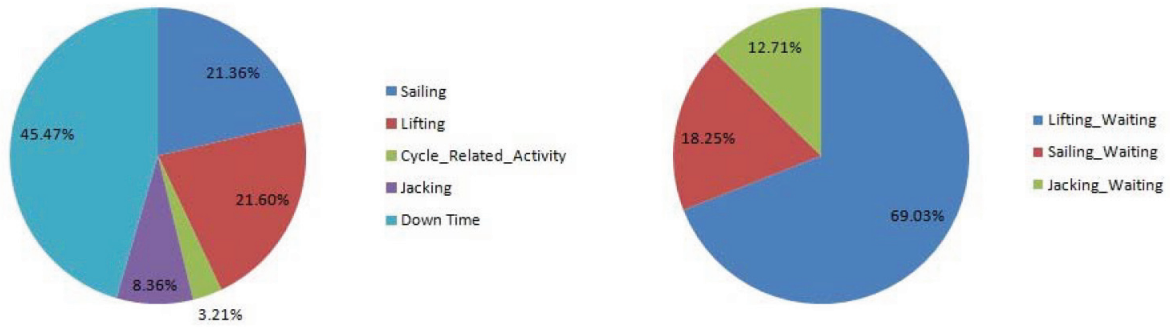

Fig. 6: The percentage of the time spent for different activities under the categories of sailing, lifting, cycle-related activities, jacking and down time (Q50)

Fig. 6 depicts the percentage of the time spent for different activities (Q80) under the categories of sailing, Lifting, Cycle related activities, jacking and down time. Sailing and lifting combined represents 42.96 % of the entire project lead time and the weather down time represents 45.47 % of the lead time. Looking at the causes of the down time, 69.03 % of weather down time is caused by the lifting operation in which the wind speed is the dominant factor. When we consider the down time percentage for the average-case scenario (Q50), the down time (45.47 % of 270.93 days) has increased by 62.25 % compared to the best-case scenario (Q20) which is 33,95 % of 223,64 days.

4 CONCLUSIONS

In this study, weather down time analysis for offshore wind farm installation has been presented based on Discrete Event Simulation (DES). The weather conditions, distance matrix, vessel characteristics and installation strategy are simulated within the planning phase of an offshore wind farm and such simulation results can support the decision making process related to the transport and installation strategy. The results pointed out that the lifting operation where the wind speed is the dominant factor causes higher down time over other activities and improving the lifting operations could result in a significant reduction in the overall project completion time.

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SUMMARY

The offshore wind energy development has shown a progress in the last ten years. Distance from the coast line and the depth of the water are getting increased from time to time. The transport and installation of offshore wind turbines is highly dependent on weather condition at sea. Any disturbance along the logistics chain could result in a significant delay in the project completion.

The purpose of this paper is to carry out a weather down time analysis for offshore wind turbine transport and installations considering the weather restriction criteria for each activities along the logistics chain. A Discrete Event Simulation (DES) model has been developed taking the vessel characteristics, distance matrix, installation methodology and sequence of activities into account. The results pointed out that the lifting operation causes higher down time over other activities and improving the lifting operations could result in a significant reduction in the overall project completion time. This paper also gives an insight how a simulation weather down time analysis could improve the decision support system in the offshore wind energy development industry at the planning phase.

RÉSUMÉ

L'énergie éolienne offshore a beaucoup progressé ces dix dernières années. La distance au large et la profondeur d'eau auxquelles ces champs sont installés ont ponctuellement augmenté. Or le transport et l'installation d'éoliennes offshore dépend fortement des conditions climatiques en mer, si bien que la moindre perturbation de la chaîne logistique peut engendrer des retards importants quant à l'achèvement du projet.

Cet article vise à mener une analyse des interruptions de transport et d'installation des éoliennes offshore par les conditions météorologiques, en prenant en compte les critères météorologiques restrictifs de chaque étape de la chaîne logistique. Un modèle de Simulation à Événements Discrets (DES) prenant en compte les caractéristiques des navires, la matrice de distance, les méthodes d'installation et l'enchaînement des différentes activités a été développé. Les résultats ont mis en évidence que les opérations de levage sont à l'origine de retards plus importants que les autres activités et qu'une amélioration de ces opérations de levage pourrait réduire significativement le temps total de réalisation du projet. Cet article illustre la façon dont une simulation des interruptions par les conditions météorologiques pourrait être utilisée comme outil d'aide à la décision par l'industrie éolienne au moment de la planification des projets.

ZUSAMMENFASSUNG

In den letzten 10 Jahren hat die Entwicklung von Offshore-Windparks Fortschritte gemacht. Die Entfernungen zu den Küsten und die Wassertiefen werden über die Zeit immer weiter vergrößert. Der Transport und die Montage von Offshore-Windenergie-Turbinen sind sehr stark von den Wetterbedingungen auf See abhängig. Jedwede Störung in der Logistikkette könnte zu einer erheblichen Verzögerung beim Projektabschluss führen. Der Zweck dieses Beitrags ist, Analysen für witterungsbedingte Ausfallzeiten bei dem Transport und bei der Montage von Offshore-Windturbinen durchzuführen, indem die Einschränkungskriterien für die Wetterbedingungen für alle Aktivitäten in der Logistikkette betrachtet werden. Es wurde ein diskretes ereignisorientiertes Simulationsmodell (DES) entwickelt, welches die Schiffseigenschaften, die Entfernungsmatrix, die Montagemethode und die Reihenfolge der Aktivitäten berücksichtigt. Die Ergebnisse zeigten, dass die Hebevorgänge verglichen mit den anderen Aktivitäten höhere Ausfallzeiten verursachen und dass eine Verbesserung bei den Hebevorgängen zu einer bedeutenden Reduzierung der Fertigstellungszeit des gesamten Projekts führen könnte. Dieser Artikel gibt außerdem einen Einblick darin, wie eine Simulation der witterungsbedingten Ausfallzeiten die Entscheidungsunterstützungssysteme der Offshore-Windpark Industrie in der Planungsphase verbessern könnte.

RESÚMEN

El desarrollo de la energía eólica marina ha sufrido un significativo avance en los últimos diez años. Durante este tiempo, la distancia de los parques eólicos a la costa y las profundidades alcanzadas en los mismos se han ido incrementando progresivamente. El transporte y la instalación de las turbinas en dichas ubicaciones resulta altamente dependiente de las condiciones climatológicas. Cualquier perturbación que se sufra a lo largo de la cadena logística puede conducir a significativos retrasos en el desarrollo y terminación de los proyectos. El objetivo de este artículo es llevar a cabo un análisis de la inoperatividad por causas climatológicas durante el proceso de transporte e instalación de turbinas eólicas, considerando criterios de restricción operativa por clima para cada una de las actividades que conforman el conjunto de la cadena logística. Para ello se ha desarrollado un modelo de Simulación Discreta de Eventos (SDE) teniendo en consideración las características de los buques, matriz de distancias, metodología de instalación y secuencia de actividades. Los resultados indican que las operaciones de izado provocan mayores inoperatividades que el resto de las actividades, por lo que la mejora de este aspecto redundará en una significativa reducción del plazo del proyecto en su conjunto. Este artículo también proporciona una visión sobre cómo la simulación y análisis de las condiciones de inoperatividad pueden ayudar a la toma de decisiones en la industria de la eólica marina durante las fases de planificación.