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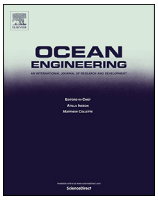

A discrete-event simulation approach to evaluate the effect of stochastic parameters on offshore wind farms assembly strategies

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ABSTRACT

The wind industry is facing new challenges due to the planned construction of thousands of offshore wind turbines all around the world. However, with their increasing distance from the shore, greater water depths, and increasing sizes of the plants, the industry has to face the challenge to develop sustainable installation procedures. Important limiting factors for offshore wind farm installation are the weather conditions and installation strategies. In this context, the focus of this research is the investigation of the most effective approach to installing offshore wind farms at sea, including the effects of weather conditions. This target is achieved through the implementation of a discrete-event simulation approach which includes the analysis of the environmental conditions, distance matrix, vessel characteristics, and assembly scenarios. The model maps the logistics chain in the offshore wind industry. A deterministic and a probabilistic metocean data method have been compared and cross validated. The results point to a good agreement between the two considered models, while highlighting the huge risks to the time and cost of the installation due to the stochastic nature of the weather. We suggest that simulations may improve and reduce these risks in the planning process of offshore wind farms.

1. Introduction

Contextualization – The offshore wind farm (OWF) is an emerging technology in the area of wind energy conversion systems. Offshore wind resources are abundant, stronger, and are more consistent in terms of their availability than land-based wind resources. The average size of an OWF connected to the grid in 2015 was 338 MW, the average water depth of a completed or partially completed wind farm was 27.1 m, and the average distance to the shore was 43.3 km, (Pineda, 2016). The European Wind Energy Association expects that by 2020, offshore wind power will account for 4%–4.2% of Europe's energy demand with an installed capacity of 40 GW, (Moccia et al., 2011; Kaldellis and Kapsali, 2013).

The potential of wind energy increases as one goes farther from the coast line (30–100 km), therefore implying greater water depths (20–50 m), higher power turbines ($\geq$ 5 MW), and stronger foundations to support the turbine components. As a matter of fact, a significantly higher energy production is achieved due to the larger wind turbine ratings and stronger wind profiles, (Sun et al., 2012). Moreover, to be economically advantageous, OWFs also have to grow in size, i.e. ~600 – 1000 new wind turbines per year (Moccia et al., 2011), and (Kaldellis and Kapsali, 2013). This will further complicate the logistical operations of the offshore wind energy systems, which require special purpose vessels with a higher deck capacity to transport the components (turbines and foundations). At the same time, cranes with good lifting capacity should also be available in order to carry out the lifting and installation operations without compromising the safety of the crew on board. This implies serious financial, technical and logistical efforts.

This explains why the power production from offshore wind is still significantly more expensive than power generation from onshore wind farms. Table 1 shows the typical cost breakdown of both onshore and offshore. As shown, most of the investment costs are related with the acquisition of a wind farm, including the wind turbines, electrical infrastructure and civil engineering work. Nevertheless, for OWFs, the installation and transport costs of an offshore wind energy plant are a significant contributor to the total initial cost and are likely to reach 20%. Therefore, the risks of over-costs and delays at the construction site, in the transport chain, and in production and storage should be carefully

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Table 1
Typical breakdown of the initial cost of a wind farm, in %, compiled and adapted from Henderson et al. (2003); Junginger et al. (2004); T. G. of the United Kingdom (2010); Davey and Nimmo (2012); IRENA (2012); Voormolen et al. (2016).

	Onshore	Offshore
Wind turbines	65–75	30–50
Electrical infrastructure	1–10	15–30
Civil work (foundations)	0–6	15–25
Installation and transport	0–3	5–30
Other	6	8

controlled.

Research gap – In addition, weather plays a critical role in offshore wind energy systems, creating a lot of uncertainties in the logistic system and the design of the foundations (whether ground based or floating). Higher wind speeds, larger waves, and the salty air contribute to a harmful environment at sea that significantly reduces the accessibility of an OWF, (Smit et al., 2007; Walker et al., 2013).

As shown in Fig. 1, there are usually 12 components that make up one complete offshore wind turbine (OWT): a jacket foundation, 4 piles, a lower tower, an upper tower, a nacelle, and a rotor comprising one hub and three blades. Whether these are pre-assembled or transported separately (the assembly scenario) has an impact on the vessel's deck space usage, crane lift requirements, and installation capability. The dimensions and weight of the components involved, e.g. blades of more than 120 m in length, make the transport and storage of the components difficult. It will also affect the time necessary to transport and install the turbine components, taking into account the suitable weather (time) windows defined by the acceptable wind speed, wave height, and sea state. All currently known mounting techniques can only be performed in calm sea. In this context, with a wave height of more than 1.5 m and/or a wind speed of 17 m/s at 10 m of altitude, the installation and transport of material at sea will generally be stopped, (Ait-Alla et al., 2013).

Importance – The installation of offshore facilities is very costly and any interruption of its supply chain could cause a big impact on the overall operation. Hence having a well-organized transport and installation system is crucial for the offshore industry. However, no tools are available that enable developers to perform a robust simulation to derive comprehensive strategies for deployment and installation. To avoid supply chain bottlenecks and to provide an effective decision support tool, an integrated and comprehensive simulation platform of the installation of OWFs that takes into account the effects of the weather is required. Indeed, the simulation of different installation strategies can support the planning process and reduce the risks to the assembly of an OWF.

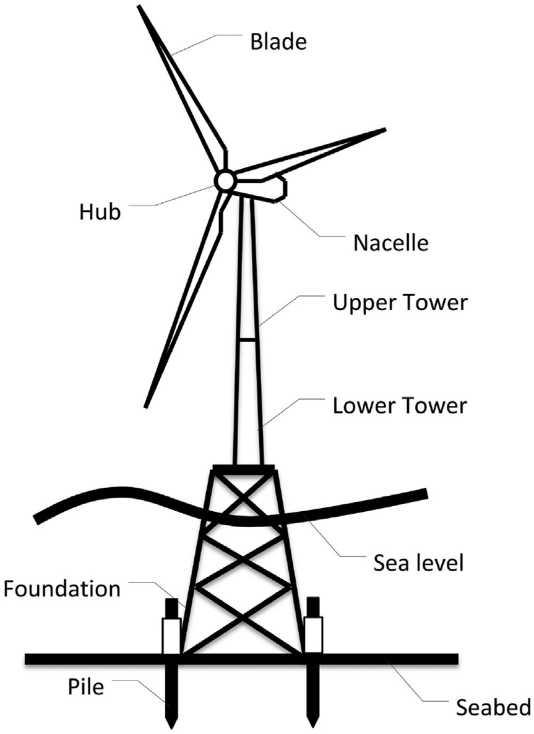

Fig. 1. Offshore wind turbine components.

Purpose – The focus of this paper is on designing and developing a discrete-event simulation (DES) model of the installation of an OWF that allows the identification of favorable installation strategies. The aim is to provide decision support to integrators trying to plan the installation of a portfolio of OWTs (20–70) in the mid-term (one to three years).

The model builds upon the existing literature by taking into consideration the distance between ports and the OWT installation sites, as well as sea state parameters. The results of a deterministic and a probabilistic metocean data module have been compared. For the purposes of illustration, both models are based on metocean time series measured between January 1995 and December 2008.

The model is able to take into account the effects of weather on the installation cycle, to assess the likelihood of delays of a certain process, and to propose alternatives to minimize the effects of these delays. By evaluating different sets of weather data, the overall installation process can be optimized with respect to shortest installation times and highest robustness of the schedule.

Outline – The outline of this paper is as follows. Section 2 reviews common procedures, aspects and issues associated with the installation of OWFs and the existing practices coupling stochastic simulations with weather models. The method and the modelling are explained in Section 3, then the results and a discussion of the case study are presented in Section 4. Lastly, recommendations and conclusions are provided in Section 5.

2. Previous research coupling DES with metocean models

Research on OWFs, which until now has been carried out by various institutions, has been mainly based on the technical challenges in the design and manufacture of the facilities, (González et al., 2014). As recently discussed by (Barlow et al.,), there has been only a little research that addresses the logistical problems in the production, installation, operation and maintenance (O&M), and disassembly of offshore facilities, (Scholz-Reiter et al., 2010; Lange et al., 2012; Steinhauer, 2011; Caprace et al., 2012; Ait-Alla et al., 2013; El-Thalji and Liyanage, 2012).

Current practices for the long term planning to build an OWF are based on statistical data. However, statistical data are insufficient for the long term planning process since it does not take into account the weather factors which have a major effect on all offshore operations. According to the literature, there is no specific tool available performing a simulation to explicitly consider the scattering (randomness) of various parameters (uncertainty of weather conditions, uncertainty of task durations, types of vessel failures and maintenance scenario) as well as to simulate various scenarios regarding the deployment strategy for an OWF. This causes a large uncertainty in the time frame of the installation process, so the date of delivery cannot be predicted accurately. Therefore, this risk can only be controlled by employing some safety margin, which results in higher deployment and installation costs and/or a longer duration, which is not compatible with the development of large OWFs.

Simulation is a modelling tool widely used in operational research (OR), (Tako and Robinson, 2010). One of the most common approaches is discrete-event simulation (DES). It started and evolved with the advent of computers, (Robinson, 2005). DES represents individual entities that move through a series of queues and activities at discrete points in time. Each event occurs at a particular instant in time and marks a change of state in the system. Between consecutive events, no change in the system is assumed to occur; thus the simulation can directly jump in time from one event to the next. Since a DES does not have to simulate every time