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Offshore wind installation vessels – A comparative assessment for UK offshore rounds 1 and 2

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ABSTRACT

Marine operations play a pivotal role throughout all phases of a wind farm's life cycle. In particular uncertainties associated with offshore installations can extend construction schedules and increase the capital expenditure (CAPEX) required for a given project. Installation costs typically account for approximately 30% of the overall project cost. This study considers the installation modelling for UK offshore Wind Rounds 1 and 2 using probabilistic simulation tool. The tool is used to output time-domain predictions for the completion of key installation phases. By varying key wind farm characteristics such as distance to shore and the number of turbines, an assessment of vessel performance was completed for each round by reviewing recorded durations predicted by the software. The results provide a quantification of installation vessel performance and the associated deviations present a measure of installation risk. It is identified that the Round 1 vessels experience less weather downtime but higher variability and the Round 2 vessels perform more consistently but experience larger delays. The paper provides a structured method to identify and benchmark offshore wind installation risks, to support developers and project planners.

1. Introduction

1.1. Background

Offshore wind farm (OWF) development has increased steadily throughout the UK over the last decade and is predicted to maintain this momentum until at least 2020 (Offshorewind.biz, 2016; Renewable UK, 2016). The UK has more offshore wind turbines than the whole of the rest of Europe. 1.5 GW is currently under construction with a further 5 GW of projects yet to begin development (The Crown Estate, 2015). As turbine sizes, distances from shore increase, weather becomes more severe and water depths span beyond 30 m, the logistical challenge becomes ever more prominent for prospective developers.

Marine operations play a pivotal role throughout all phases of a wind farm's life cycle, yet uncertainties associated with offshore installation can extend construction schedules and increase the capital expenditure (CAPEX) required for a given project. Installation costs can account for approximately 30% of the overall project cost and it is anticipated informed engineering decisions in this area present further cost saving potential (Krohn et al., 2005). The increasing remoteness and heightened weather conditions for the UK's future OWFs, increases the complexity of the marine operations and the importance of making the correct decisions prior to development and sourcing of the correct vessels to complete the tasks.

At the beginning of the OWF development in the UK in 2001, the vessels used for construction introduced bottlenecks and delays in construction. This was caused by a lack in availability of specialised vessels as these were predominantly used in the oil and gas sector, introducing competition for their services. In some cases the vessels were oversized or not ideally suited to the operations, which were often sourced at over-inflated charter rates. As OWF development increased, the industry began to manufacture purpose built offshore wind vessels that would offer more deck space, cope with more severe weather and reduce overall installation durations (Offshore-technology, 2012).

This paper considers the installation modelling for UK offshore Wind Rounds 1 and 2. The analysis is based on time-domain predictions for the completion of key installation operations under user specified exceedance probabilities, commonly used by investors to determine a project's

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viability and used by developers to assess their risk preferences. By varying key wind farm characteristics, an assessment on the performance of typical installation vessels adopted for each of the UK development rounds is investigated with the use of an OWF installation decision support software tool. A comparative analysis of the predicted durations between each of the two offshore wind rounds is completed. this analysis will help inform planning operatives when considering vessel selection in their next project and reveal if further innovation is needed to overcome delays when developing future OWFs.

The remainder of the paper is structured as follows: Section 2 presents a brief literature review of the most pertinent work in this field. In Section 3, we begin with a description of the wind farm installation software and an overview of the processes applied within the tool. We then describe in Section 3.3 the various sources of meteorological data used for each round and provide a justification for their selection. The key OWF characteristics to be varied throughout the simulations is included in Section 3.4. These are applied to resemble the range of OWF sizes and remoteness, typically experienced within each round. It is also intended that these highlight the characteristics that can significantly impact the progression of offshore installation operations and where further technological innovation can be explored. Section 3.5 describes the process used to identify the typical vessel spreads used in each offshore wind round and Section 3.6 describes the fundamental OWF installation operations and their associated environmental limits. Section 4 presents an overview of the results, which are supported with discussion in Section 5, covering the outcomes by round, value to planners and future work. Finally, a summary of our findings and relevant conclusions are presented in Section 6.

2. Literature review

The work on the modelling of logistical requirements and installation of OWFs has increased over the last five years in an attempt to reduce uncertainty associated with accessing and completing work at offshore locations. This type of modelling and analysis allows practitioners to review the installation of an OWF in advance, so that developers can prepare for certain outcomes in terms of cost or delay.

Many authors focus on the modelling of the construction operations and subsequent weather risk analyses. Irawan et al. (2015) look to address the scheduling issues surrounding offshore wind construction by means of an integer linear programming method to identify the optimal installation with lowest costs and shortest schedules, combining weather data and vessel availability. Their investigation in the use of meta-heuristic approaches such as Variable Neighbourhood Search (VNS) and Simulated Annealing (SA) was found to offer reasonable results with low computation time. Their approach is compared against a linear programming optimiser known as CPLEX, which is found to identify the optimum solution but takes longer to reveal the answer.

Others have considered the specific modelling of the logistics surrounding the installation steps, where Barlow et al. (2015) review what vessels and operations are most susceptible to weather constraints during the installation campaign. Their study aims to assess the impact of operational and vessel improvements over recent times, indicating that a non-linear relationship exists between vessel limits and the duration of the installation. It is also concluded that load out operations appear most susceptible in adverse weather conditions.

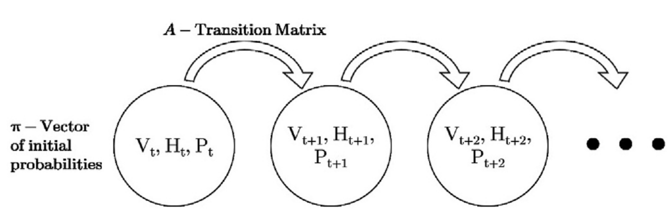

Fig. 3.1. Schematic representation of the Markov Chain: Wind Speed (V_t), Wave Height (H_t), Current Speed (P_t).

Logistics are again the topic in the paper presented by Vis and Ursavas (2016) where their modelling approach reveals that the key activities impacting performance are the vessel loads, distance to shore and the pre-assembly strategy adopted for the main wind turbine components. They recommend that a pre-assembly strategy should be employed that presents the optimum choice between the lowest number of lifts possible and the maximum number of turbines that can fit on a vessel. This reflects that the optimum will differ in each offshore wind project but careful consideration of these two parameters should help reveal the best solution for a given project.

Scholz-Reiter et al. (2011) point out that bad weather conditions are the main cause for delays in the logistics and installation of an offshore wind farm. They apply their mixed integer linear programming (MILP) model to identify the optimal installation schedule for different weather conditions and the loading operations. Their study considers the installation of 12 turbines across three synthetically produced weather scenarios, each representing either good, medium or bad weather and the tool is used to identify optimal installation schedules for the vessels. They acknowledge the stochastic nature of weather conditions and express an interest in developing their tool and assess the impact of weather uncertainty beyond these initial three categories.

Ait-Alla et al. (2013) developed a MILP model to minimise the installation costs by considering vessel utilisation and fixed costs that span the length of the installation period. Their approach considers the weather in a deterministic manner and reviews the outcome of two installation scenarios.

Muhabie et al. (2015) consider the use of discrete event simulation by considering weather restrictions, distances, vessel capabilities and assembly scenarios. They consider the use of real historical weather data and generated data sets adopting a probabilistic approach. The results demonstrate a good level of agreement between the two approaches when considering the average mean lead-time and reference future work to optimise the fleet sizes, capacities and overall installation strategies.

This paper evaluates the installation durations and subsequent vessel performance during the construction of an OWF. A probabilistic function to simulate the weather is enclosed within the adopted tool, which is capable of producing a range of results under user specified exceedance probability quantiles. The user defined exceedance quantiles provides an assessment of installation risk at different confidence levels. This presents a key benefit over the tools reviewed in this section as it offers the adaptability to planners and investors as required. The tool can simulate the full installation of an OWF, handled in phases and considers the environmental constraints of the operations and vessels across the predicted weather outcomes.

3. Methodology

This paper employs an offshore wind installation software simulation tool to determine the installation duration of an Offshore Wind Farm (OWF) in advance. Moreover, a focus on the predicted performance of vessel technology, synonymous of typical vessel spreads used throughout the first two UK offshore wind rounds, are analysed to identify the variation in installation durations and weather downtime.

3.1. Wind farm installation software

The software tool relies on Monte Carlo methods to simulate multiple independent scenarios of the defined installation strategy for an offshore wind farm. The tool considers risk as delays to the installation, imposed by adverse weather conditions. A HMM model (Rabiner and Juang, 1986) has been used to generate each meteorological scenario informed historical weather data, which begins with the evaluation of a transition matrix A for the Markov chain. This matrix represents the evolution of the weather parameters: wind speed (V_t), wave height (H_t) and speed of the sea current (P_t). In this study, the wind speed and wave height are the

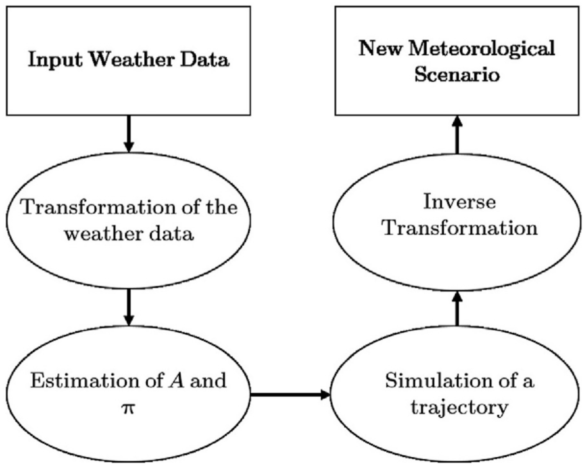

Fig. 3.2. Schematic of the principal method.

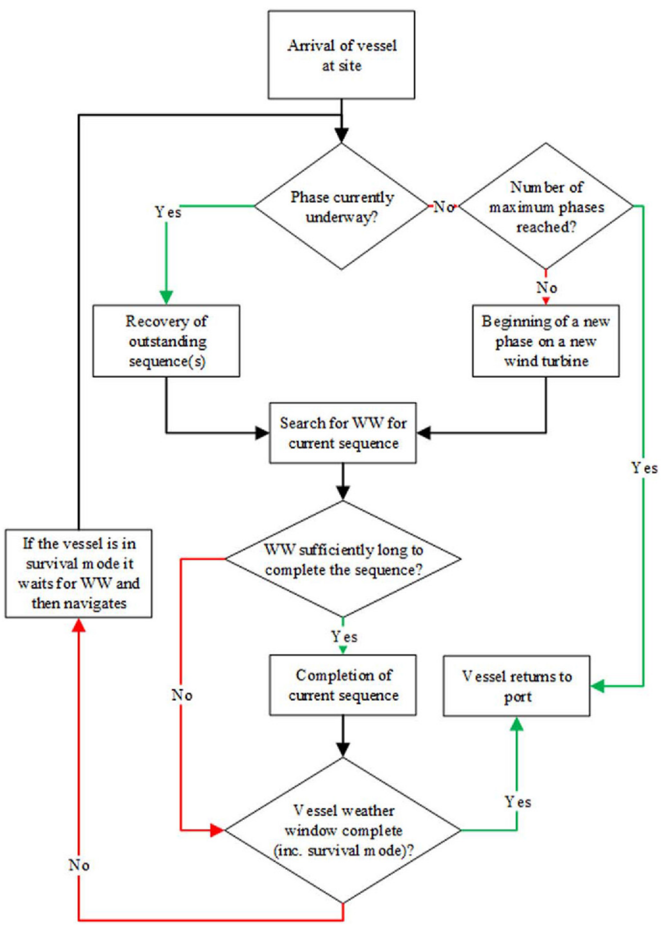

Fig. 3.3. Flowchart of logistical process.

only weather conditions evaluated. Meteorological parameters are intrinsically stochastic but also exhibit some continuity over time. Therefore, at any one time, if the sea is in a certain state, it is more likely that the next time (one hour, for example), the sea remains in a similar state. The main characteristic of a Markov chain is that the next state depends only on the state at the current point in time, which is described by Fig. 3.1. If the probability of moving from one state to another are known, then it is possible to generate meteorological parameters and thus to obtain a new weather scenario.

Each element of the transition matrix A, is the probability for the arrival of state j is knowing the initial state i. A is a matrix of size $n*n$ with n the number of states of the Markov chain. The vector π of the initial probability array of the hidden states is also determined for chain size n. It is possible to obtain empirical estimates of this matrix and vector by:

$$A = (a_{i,j})_{1\le i,j\le n} \quad \textbf{and} \quad \pi = (\pi_i)_{1\le i\le n}$$

where:

$$a_{i,j} = \frac{number\ of\ transitions\ i \rightarrow j}{number\ of\ transitions\ from\ i}$$

and

$$\pi_i = \frac{number\ of\ observations\ in\ the\ state\ i}{total\ number\ of\ observations}$$

For a given initial state, the number of arrivals of possible states is relatively low at a maximum of 30. Thus the matrix A, contains many zeros and forms what is called a matrix dig. For each initial state i, it is best to store only the non-zero values $\widetilde{A}(i)$ and associated indices $P(i)$, which is defined as:

$$P(i) = j|a_{i,j} > 0 \quad \textbf{and} \quad \widetilde{A}(i) = (a_{i,j})_{j\in P(i)}$$

Once the estimated transition matrix is established, the software will simulate a weather scenario over a period specified, which corresponds the maximum installation duration envisaged by the user. The software simulates the weather at the time $i+1$ knowing the state of the weather at the time i according to transition matrix. The method relies on a monthly transformation in the data in order to 'normalise' the environmental data to a stationary form, which is inspired by Dinwoodie et al. (2012). The transformed data is assumed to be embodiment of a Markov chain and the matrix A, and the vector π are estimated on these transformed data. After the simulation of the Markov chain is applied to reconstruct the monthly outcomes into one meteorological scenario. An overview of these steps is demonstrated by Fig. 3.2.

$X_{i.k} = (X^{(1)}_{i.k}, X^{(2)}_{i.k}, X^{(3)}_{i.k})$ is regarded as the vector of three meteorological parameters for the i-th observation, during month number $k, k \in \{1, 2\ldots, 12\}$. The monthly processing carried out in the method is as follows for each of the parameters $h\{1, 2, 3\}$

$$y^{(h)}_{i.k} = \frac{X^{(h)}_{i.k} - \mu^{(h)}_{i.k}}{\sigma^{(h)}_{i.k}}$$

Where $\mu^{(h)}_{i.k}$ and $\sigma^{(h)}_{i.k}$ are the mean and standard deviation of the parameter number h over the month number k. The meteorological parameters are supposed to take their values in a discrete space and have a finite number of states.

A given meteorological scenario is used directly within each Monte Carlo simulation to calculate a duration for each primary installation phase. Eight installation phases are considered within this study, which are as follows: Dredging&Survey, Foundation, Transition Piece, Turbine (WTG), Scour Protection, Pre-lay Grapnel Run (PLGR), Cable Installation and Cable Burial. These phases include sequences that comprise of subtasks, elementary to the operations. The tool allows phases to be suspended once a sequence has been completed and uses their base duration to determine if an adequate weather window is available, or if the vessel should hold station offshore. A weather window can be defined simply as weather conditions that are predicted to stay within the environmental limits of a sequence, for a specified duration.

Once the software has computed the predicted durations, these can be processed to reveal the average Installation Rates (IRs) and weather downtime (WDT) for each of the installation phases. The P90 exceedance quantile was selected as the referenced result category, providing 90%

Table 3.1
Round 1 OWF characteristics.

Parameter	Maximum	Mean	Minimum
No. of Turbines	60	31	2
Expected Start Date	01/04/2017	01/08/2017	01/12/2017
Inter-turbine distance (km)	0.82	0.67	0.46
Distance to shore (km)	11	6	2

Table 3.2
Round 2 OWF characteristics.

Parameter	Maximum	Mean	Minimum
No. of Turbines	175	93	18
Expected Start Date	01/04/2017	01/08/2017	01/12/2017
Inter-turbine distance (km)	1.08	0.84	0.63
Distance to shore (km)	40	19	7

confidence that the predicted durations will not be exceeded. The numerical results allow the calculation of Key Performance Indicators (KPIs). In this study we use the duration for each phase divided by the number of wind turbines associated to the given model to reveal an average IR in days per turbine (Days/WTG). Similarly, the base unweathered duration for each installation phase is deducted from the predicted duration to reveal the average weather downtime (WDT) that can be expected for each turbine location under the individual phases. These IRs and WDT values can then be generally compared between the rounds to assess the impact of vessel technology. Additionally, the variation about the mean IR and WDT predictions, can be used to estimate the installation risk that may be anticipated for each installation phase.

3.2. Model calculations

A high level description of the methodology applied within the tool for the execution of installation phases is as follows. Firstly, the ship to be used for an installation phase is mobilised. The vessel goes offshore as soon as it's shipping weather limits are satisfied. Next the logistics model, as outlined in Fig. 3.3 is used to apply the phases considering the make-up sequences within each phase. This process initially recognises phases that were not completed in the previous weather window and the process begins at the first of the remaining sequences, otherwise the tool identifies the maximum number of phases to be handled by the vessel and if it is within these bounds, the process begins with the next phase in hand. It is determined if a weather window exists, where the environmental limits of the next sequence are satisfied for the corresponding duration. If the conditions are not satisfied, the software continues to search for a suitable weather window and whilst none are available, the vessel holds station. This stands unless the weather conditions become worse than the waiting condition limits for the vessel, meaning the vessel returns to port and awaits the next opportunity to set sail to site.

The completion of each sequence marks the end of the weather window search and the tool assesses if the vessel can remain on site, either by the maximum number of phases or by the predicted weather conditions. Again, if poorer weather is predicted and the environmental limits allow, the vessel can hold station. If the vessel is in the middle of a current phase or there are phases to complete, the process starts over and searches for a window to complete the next sequence. This iterative process continues and is applied to all installation phases until they are complete for each wind turbine, after which the vessel for the given phase is demobilised and the next vessel begins the subsequent phase in the defined schedule. Finally, the process is complete when the maximum number of Monte Carlo simulations has been reached. The predicted durations for each installation phase are presented with a start and an end date. These dates are recorded under user specified exceedance quantiles such as P50, P70 and P90. It is these predicted durations that are used as the main source of results in this study, as presented in Section 4.

3.3. Meteorological data

Meteorological data was obtained from separate hindcasts used for the two offshore wind rounds. In each simulation, a single metocean time series is used to inform the HMM, which generates 1000 stochastic weather scenarios. These scenarios provide a basis to assess the progression of the installation phases by considering the environmental limits of the sub-tasks and vessels specified for each round. Data from Teesside and Greater Gabbard was selected, representing the conditions of Round 1 and Round 2 sites respectively. The wind speeds in each data set are referenced at 10 m. Teesside offshore wind farm is located off the north east coast of England and its near shore location is synonymous of a Round 1 project. The data set was developed by a private consultant, drawing on field and modelled data to construct a metocean time series. For Round 2, publicly available data for the Greater Gabbard offshore wind farm was sourced from The Crown Estate's Marine Data Exchange (The Crown Estate, 2015). Greater Gabbard is located off the English Suffolk coast and is close to the average distance of all Round 2 sites.

3.4. Wind farm characteristics

The key OWF characteristics for each project within the two offshore wind rounds have been reviewed based on the information included in Renewable UK (2015). This identified mean, maximum and minimum characteristic values across all of the OWFs in each round. The characteristics varied within the simulation tool and the values identified for each round, are listed in Tables 3.1, 3.2. For each OWF round, 11 cases were simulated, beginning with a mean case for all parameters and then varying one parameter at a time with either a maximum or minimum value. Two 'extreme' cases are included, comprising of maximum and minimum case for the number of turbines and distance to shore combined. To consider the impact of start date selection, three dates were selected to investigate the impact of seasonality across the two rounds. April was chosen to resemble construction beginning in the spring, August for summer and December for a winter start.

3.5. Vessel technology&spreads

An assessment of the vessels used across all of the OWFs within the consenting rounds in Renewable UK (2015), was completed to identify

Table 3.3
Vessel types and spread by round.

Phase	Round 1		Round 2	
	Vessel Type	Ref.	Vessel Type	Ref.
Dredging&Survey	Injection Dredger	Van Der Kamp (2015)	TSHD	Royal Boskalis Westminster (1999)
Foundation	WTIV	MPI Offshore (2016)	Heavy Lift Vessel	Seaway Heavy Lifting (2016)
Transition Piece	WTIV	MPI Offshore (2016)	Floating Crane	Van Oord (2015)
WTG	Jack-up Barge	A2Sea (2013)	WTIV	MPI Offshore (2016)
Scour Protection	Rock Dump	Peter Madsen Rederi (2013)	FPV	DEME Group (2014)
PLGR	Multicat	Damen Shipyards Group (2016)	Offshore Vessel	Peter Madsen Rederi (2013)
Cable Inst.	Barge	Ugland Construction AS (2006)	CLV	Royal Boskalis Westminster (2014)
Cable Burial	MPSV	Van Oord (2015)	MPSV	Fugro (2016)

Table 3.4
Task durations and operational limits.

Phase	Reference Duration (h/WTG)	Max. Wind Speed (m/s)	Max. Wave Height (m)
Dredging&Survey	48	11	1.5
Foundation	48	12	2
Transition Piece	24	12	2
WTG	24.5	8	2
Scour Protection	14.4	15	2.5
PLGR	14.4	20	2
Cable Inst.	31.7	15	1.5
Cable Burial	36	12	3

the typical vessel spread used at the time of installation. It is accepted that the categorisation by UK Offshore Wind rounds does not mean all construction activities were completed within an allocated time frame as some Round 2 sites were installed before Round 1 projects, however this classification was adopted to gauge the impact of step changes in vessel technology.

To identify the main vessel types used to install or planned for installation of each OWF, reference to the vessel listings for each respective wind farm on 4C Offshore were used to populate a vessel database for each round (4C Offshore Ltd, 2016). Using the parent installation phases as a guide, the vessel database for each round was then assessed to reveal the most common vessel type chartered for each phase, which produced a representative vessel spread for each round. It should be noted that the vessel spreads for each round, included in Table 3.3, are based on the transparency of information published on the 4C Offshore website. The provided references give more detail on the general vessel type, and a full list of vessel characteristics used in the study are appended in Table A.1. For each vessel type identified and listed in Table 3.3, the referenced vessel specifications were used to generate approximations for the loaded and unloaded transit speeds in conjunction to survival limits for wave height and wind speed. Where some environmental limits were not listed on the specification sheets, generic references or limits for similar vessels were used to approximate the relevant values (Dalgic et al., 2015; Douglas Westwood, 2013; Sperstad et al. 2016; Thomsen, 2012; Van Oord ACZ, 2001). Whilst this information is sufficiently detailed for modelling, analysts will have more specific information from the vessel operators to plan the marine operations. The commissioning phase of the wind farm, which predominantly adopts crew transfer vessels (CTVs) to transfer technical personnel to the turbines, has not been considered.

Eight offshore installation phases are considered for analysis and are summarised in Table 3.3, which specifies the installation phase and vessel used in the model set-up. It should be noted that all vessels are assumed to have the capacity to remain offshore to complete the work at all turbine locations, with the exception of the vessels used for the foundation, transition piece and WTG installation phases, which are limited to a maximum of three turbine locations per voyage. This limitation is discussed further in Section 5.4.

Each phase and vessel choice for the different rounds are described in the following passage. The dredging&survey phase prepares or clears the seabed before the main OWF construction activities begin and ensures the work has been completed to a sufficient standard. Dredging is not required for all projects but has been included to acknowledge some form of seabed preparation common to many sites. It is assumed that the dredging phase follows on from and is prescribed by, an extensive seabed survey. This is completed well in advance of the main construction activities to inform project teams of any unexploded ordnances, potential obstacles, seabed integrity, the applicable foundation type(s) for the site and the extent of dredging operations required. A dredge vessel can be fairly simple, consisting of a barge equipped with a backhoe excavator to more advanced dynamically positioned (DP) vessels that include trailing suction hopper technology (TSHD) (Kaiser and Snyder, 2012). Less sophisticated dredgers were used in earlier UK projects, but as installations have moved further from shore, developers have discarded traditional monopile foundations for gravity based or jacket structures. This requires improved accuracy and subsequent manoeuvrability of the dredge vessels, demanding the most advanced technology available to developers.

The second phase considered is the foundation installation phase. From review of the vessels used for foundation works in both rounds, it is evident that different types of vessels have been employed to deal with the variation or trends in foundation type used between rounds (Renewable UK, 2015). The majority of Round 1 sites adopted monopile foundations as these could be installed quite easily in the nearshore locations synonymous with the majority of these sites. This type of installation can be handled on board jack-up barges and dedicated wind turbine installation vessels (WTIVs) and this type of vessel was identified as the most common vessel in Round 1. Round 2 sites are generally greater in size and located further from shore, leading to more challenging conditions for installation. This shift presented further logistical challenges and often heavy lift vessels that could deliver and install foundations were employed to reduce materials handling at the offshore locations

The installation of the transition piece, which is the structural section that links the monopile and wind turbine, is the next installation phase. The transition piece provides a fendering area for crew transfer vessels to interface with the structure and a ladder for personnel to climb onto the platform before entering the turbine for either construction or maintenance tasks. It is common that the transition piece is prefabricated onto a jacket or tripod foundations, but it is assumed that monopile configurations are used for the installation campaigns considered throughout in this paper.

The wind turbine installation phase was found to adopt some form of dedicated WTIV across in both rounds. These vessel types incorporate four to six legs that rest on the seabed and elevate the main body of the WTIV above the water. This protects the vessel from wave heights between 1.5 – 3 Hs, depending on vessel design, and helps stabilise the lifting operations. These vessels are also used to transport between three to eight turbines at a time, depending on the available cargo capacity and the installation strategy adopted. As indicated in Section 3.5, the turbine installation vessel has an assumed capacity of three turbines per voyage. The whole lifting process remains sensitive to the conditions, particularly wind speed and when individual blades or assembled rotor sections are hoisted, the environmental limits are often lowered. A number of different WTG installation strategies have been used in various projects as presented in Kaiser and Snyder (2012). These range from individual sub-section lifts for the towers and single blades, through to fully assembled turbine lifts. It is assumed that the lifting strategy is identical in both rounds to limit the amount of modelling permutations considered.

The 'bunny-ear' configuration with a 2 stage tower lift was selected as the most applicable strategy as this presented a compromise between fully assembled and an individual component installation. In this installation strategy the maximum and minimum tower sections are connected on land, as with the rotor, which is pre-assembled, consisting of a nacelle and 2 blades attached. This results in a total of three lifts at the turbine location beginning with the tower, then rotor and finally the third blade (Maples et al., 2013). It should be noted that the reference duration in Table 3.4, represents the approximate time to install each turbine using in the bunny-ear configuration and this figure would fluctuate for each of the installation strategies presented in Kaiser and Snyder (2012). In Round 1, jack-up barges without their own means of propulsion were commonly used. These vessels often have modest elevation heights and are dependent on other vessels such as anchor handling tugs (AHTs) to transit and manoeuvre the barge to each wind turbine location. Self-propelled jack-ups started to be used in Round 1 but were more commonly chartered for Round 2 projects. This next stage in WTIV design presented improved manoeuvrability, elevation heights and deck space, offering improved cargo capacities and logistical options.

Scour protection is installed to prevent structural instability around

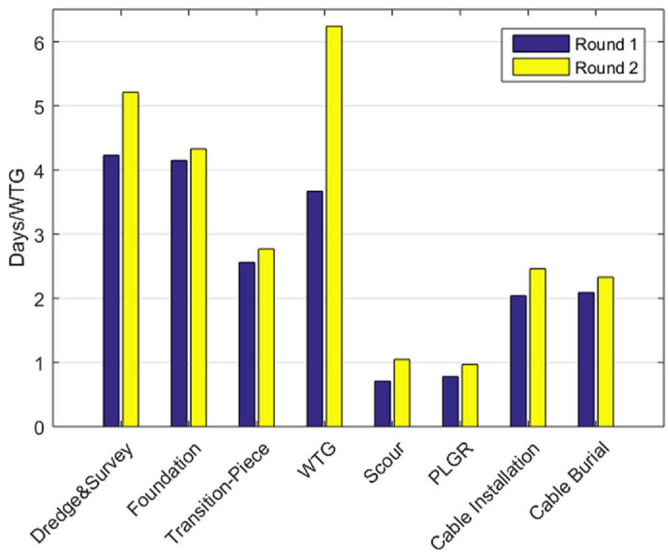

Fig. 4.1. Average Installation Rate in Days/WTG (or WTG Location) [± 1 S.D.].

the foundation of an offshore wind turbine, induced by tidal flow or wave action. The specific solution depends on the foundation selected, the long-term meteorological conditions and the seabed material. Rock-dumping is often used to place variable grades of stone around foundations or protection is placed over vulnerable cable lengths in the form of concrete mattresses. This phase can be completed with a hopper barge and towing tug or more commonly with a dedicated side stone dumping vessel or with more sophisticated fall pipe vessels (FPV). It is assumed in these analyses that the scour protection is installed around the base of the mono-pile foundations.

The pre-lay grapnel run (PLGR) is used to clear debris along the cable route before installation, ensuring that hazards do not interfere with cable laying and burial phases or during future maintenance operations (Offshore Wind Programme Board, 2015). A hook like anchor is pulled during this process and relies on the forward motion of the vessel to work the seabed, creating a narrow trench of approximately 1 m depth along the cable route. A multi-purpose workboat with a bollard pull of roughly 20 tons, is normally used for this activity.

Cable laying operations require a dedicated cable lay vessel (CLV) to lay the inter-array cables between the turbines and export cable to the onshore substation or from the offshore substation to the cable landfall point. Earlier projects often employed adapted barges that feed out cable from a pre-installed cable carousel due to the near shore, sheltered conditions (Energy Institute, 2014). These rely on other vessels to tow and install anchoring arrangements to keep the barge to the designated cable path as these vessels are not equipped with dynamic positioning (DP) systems. It is assumed that this type of installation was used for the Round 1 project and is modelled with a transit speed that resembles the speed of an AHT, of between 6 and 8 knots. In some instances an adapted supply vessel was used to take advantage of the DP capabilities but for the majority of the Round 2 projects, specifically designed CLVs were employed to cope with more extreme conditions and exposed cable routes. Many of these vessels can handle simultaneous laying, trenching and burial operations but often a secondary vessel is assumed to complete the trenching and burial phases (Bard and Thalemann, 2011).

The cable burial phase is assumed to enclose both the trenching process and final burial of the cable. The study also assumes that a post-lay burial operation is applied in both rounds utilising a secondary multi-purpose support vessel (MPSV) or large survey vessels. This 'lay and trench' technique deploys an ROV from the parent multi-purpose vessel to trench around and bury the cable in one operation. The main logistical steps of this phase are assumed to relate to the parent multi-purpose vessel and a burial duration was selected on a per wind turbine basis.

3.6. Operations, environmental limits&durations

To assess the vessel technology from Round 1 and 2, a set installation scenario is used, presented in Table 3.4. To resemble a typical installation programme, a number of the phases were set to run simultaneously. The Foundation phase was specified to begin once the Dredging and Survey phase had reached 60% completion, the Transition Piece installation began when 40% of the Foundation phase was completed, Turbine installation began after 20% of the foundations were installed, Scour Protection follows at 80% of completion, 100% for the PLGR phase, Cable Installation at 60% of the PLGR Phase and Cable Burial only begins after the Cable Installation had completed to 100%.

Each of the main installation phases were allocated with environmental limits, independent of the associated vessel restrictions and resemble the maximum conditions that can be experienced when completing these offshore operations, separate from vessel capabilities. The same task parameters are assumed in both rounds, which are to the author's best knowledge and experience, a fair representation of the expected values for these installation operations. It is reiterated that separate environmental limits exist for the different vessels in terms of transit and waiting modes. As soon as the weather conditions are below a vessel's transit limits, the vessel will set sail to the offshore site. The transit time is calculated simply by dividing the distance between the farm and the port by the vessel speed. If at any point, the weather conditions exceed the transiting limits during an outward or inter-turbine voyage, the vessel returns to port. When the transit duration has been completed, the vessel is on site and the software calls on the limits and durations applied to the installation phases. This determines if a sufficient weather window exists to start an installation sequence or if the vessel should wait for the next available weather window, if the waiting conditions of the vessel are satisfied.

Three main characteristics are used for each installation step within the models: 1. Reference Duration (average number of hours spent per WTG), 2. Maximum wind speed (m/s) and 3. Maximum wave height (m). Reference to available literature such as (Maples et al., 2013; Douglas Westwood, 2013) and in-house planning documentation was used to establish the base installation durations, wind speeds and wave heights for each phase listed in Table 3.4.

4. Results

To assess the impact of vessel technology on construction durations for offshore wind farms, the scenarios in Section 3.4 were applied using the simulation tool described in Section 3.1. For both wind rounds, 11 cases were constructed, initially taking one mean case of all parameters, eight cases where each parameter was run with an maximum and minimum value in turn, and two extreme cases combining a maximum and minimum situation for the number of turbines and distance to shore. The main characteristics of the vessels under analysis are the transit and survival limits, which are composed of a maximum wave height and wind speed as listed in Table A.1. The transit speeds of each vessel for loaded and unloaded states are also specified. An overview of the vessel spreads used for each round is included in Table 3.3.

Each simulation is run for a 1000 iterations to obtain sufficiently accurate results. The average simualtion time for a round one case was 1 day and 1.6 days for round two. For each of the individual 11 cases, the software produces a calendar output for all installation phases, recorded under user specified exceedance quantiles. The predicted duration for each installation phase is presented with a start and an end date, meaning the results are rounded to the nearest day. The P90 duration quantile was selected for analysis in this study, as it provides greater certainty that the predicted values will not be exceeded when conducting these type of operations offshore. The predicted P90 duration for each phase are divided by the number of turbines specified in each case, to reveal the average installation rate (IR) in days per turbine (Days/WTG). The IR represents the average number of days required to complete the

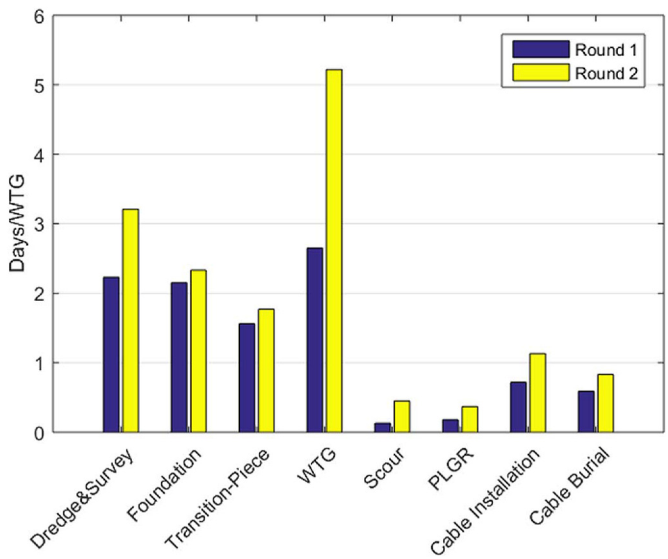

Fig. 4.2. Average Weather Downtime in Days/WTG (or WTG Location) [± 1 S.D.].

installation task at each turbine in the model, including the impact of weather delay. To demonstrate how these results can be used in practice, an average result for weather downtime (WDT) is calculated by deducting the base duration from the predicted P90 duration for the phases in each case. The base duration in each phase is calculated using the net time to complete the installation tasks without the impact of weather delay, and multiplying this by the number of turbines in each case. The resulting WDT duration is once again divided by the number of turbines for each case, to reveal a WDT value for the individual installation phases in Days/WTG.

Within each case eight IR and WDT values are collected, corresponding with the number installation phases. For each round, a total of 11 cases were collected and an average IR and WDT for the eight installation phases, was computed from this compilation, as shown in Figs. 4.1 and 4.2. As discussed in Section 3.1, the deviation from these averages is regarded as a means to estimate the installation risk in the potential outcomes.

Box plots that show the variation in the results are presented in Figs. 4.3a to d and a comparison of the recorded variation in each phase in both rounds, is included in Fig. 5.3. The greatest variability in the results were observed for the Foundation, Transition Piece and Wind Turbine installation phases, as represented by the larger bars in Fig. 5.3. This indicates that the greatest risk is estimated to occur within these phases, although the Round 2 figures demonstrate lower deviation despite higher durations.

4.1. Results overview

The IR for each of the eight phases was used to compare the differences between the vessel spreads of each round. Fig. 4.1 presents a summary of the installation rates in days per wind turbine (Days/WTG).

The results in Fig. 4.1 show that Round 1 is predicted to have the smallest IRs, with the largest recorded for the dredging and survey, foundation and WTG installation phases, predicted to be around 4.2, 4.1 and 3.6 Days/WTG respectively. The results for Round 2 show the greatest IRs and the largest are again recorded for the same phases at 5.4, 4.4 and 6.3 days/WTG respectively. It can be generalised that Round 1 appears to outperform Round 2 vessels in terms of installation rate, by approximately 25% on average across the eight installation phases. The biggest difference between Round 1 and 2 is seen with the Dregde&Survey phase at around 1 Day/WTG and the WTG installation phase at approximately 2.5 Days/WTG.

As a direct consequence of the results presented in Fig. 4.1, knowing the base duration for each of the installation phases allows for the amount of WDT to be identified. The weather delay expected on average for each phase between the two rounds, is presented in Fig. 4.2. This confirms that the greatest delays are observed in the Round 2 phases. This process presents a method for predicting the average WDT for each installation phase. If this approach was used to analyse a case specific simulation, built to match the characteristics of a prospective development, this would provide a basis to scale the results by the number of turbines and reveal an approximate overall WDT for each installation phase.

4.2. Results by round

The results for the individual rounds were further analysed to determine the distribution of phase durations predicted by the software. The box plots of the IRs and WDTs in each round have been aligned in Figs. 4.3a to d. In terms of WDT, Figs. 4.36c and d demonstrate the same range of distribution as the IRs, but at lower values. A plot of the quantification of the inter-quartile ranges for the IRs and WDTs from each phase across the two rounds, is included in Fig. 5.1.2 and is used to demonstrate the spread in the results, which can be used to signify the installation risk for the combined vessel-phase configurations. This is calculated by simply subtracting the bounds of the first quartile from the third quartile, for each of the installation phases in Rounds 1 and 2.

Fig. 4.3a demonstrates a considerable range for the installation phases in Round 1, particularly in the Wind Turbine (WTG), Transition piece and Foundation installation steps, as demonstrated by the broad space taken by the interquartile range (IQR). The variability of these IRs span from approximately 2.4 to 5.5 Days/WTG with an IQR of about 3 Days/WTG for the Foundations, 1.4 - 3.9 Days/WTG with an IQR of 2.3 Days/WTG for the Transition Pieces and 1.9 - 5.3/WTG days with an IQR of 3.4 Days/WTG for the turbines. All of the phases demonstrates a skew towards the upper values of the data. The Dredging&Survey, Cable Installation and Cable burial phases exhibit lower variance in the results and a nominal range was predicted for the Scour and PLGR stages, with the majority of these phases taking 1 day or less per wind turbine.

Fig. 4.3c shows similar variance between the Round 1 IR and weather downtime predictions (WDT). Based on the results in Fig. 4.3a, it can be expected that the greatest ranges would be seen at the Foundation, Transition piece and Wind Turbine installation phases at 0.4 - 3.6 Days/WTG with an IQR of 3 Days/WTG, 0.4 - 2.8 Days/WTG with an IQR of 2.3 Days/WTG and 0.8 - 4.3 Days/WTG with an IQR of 3.2 Days/WTG respectively. Again, the medians for these phases are skewed towards the upper data in the plots. The distribution of all phases in Fig. 4.3c have a near identical profile as seen the IRs. The Scour and PGLR phases are predicted to have the lowest WDTs and subsequent WDT in Round 1 without much variation, while the three key phases of the Foundation, Transition Piece and Wind Turbine installation present the highest values in terms of delay.

Fig. 4.3b shows generally smaller ranges for the results when compared to Round 1. The broadest IQR distributions relate to the Dredging&Survey, Transition Piece and Wind Turbine phases at 0.5, 0.4 and 0.45 days/WTG respectively. The Foundation and Transition Piece installations have an overall range of approximately 2 Days/WTG and the largest recorded for the WTG installation at 4 days/WTG. The same distribution profiles are again replicated in the WDT plots shown in Fig. 4.3d and once more the Scour Protection and PLGR phases demonstrate the lower weather downtime. The Dredging&Survey, Foundation and WTG installation phases are shown to have the largest values in terms of WDT. Generally, it was found that the installation rates and WDT predicted for the phases in Round 2 are higher in comparison to Round 1. However the results seem more consistent as the distributions are quite narrow and this smaller variation indicates a reduction in installation risk.

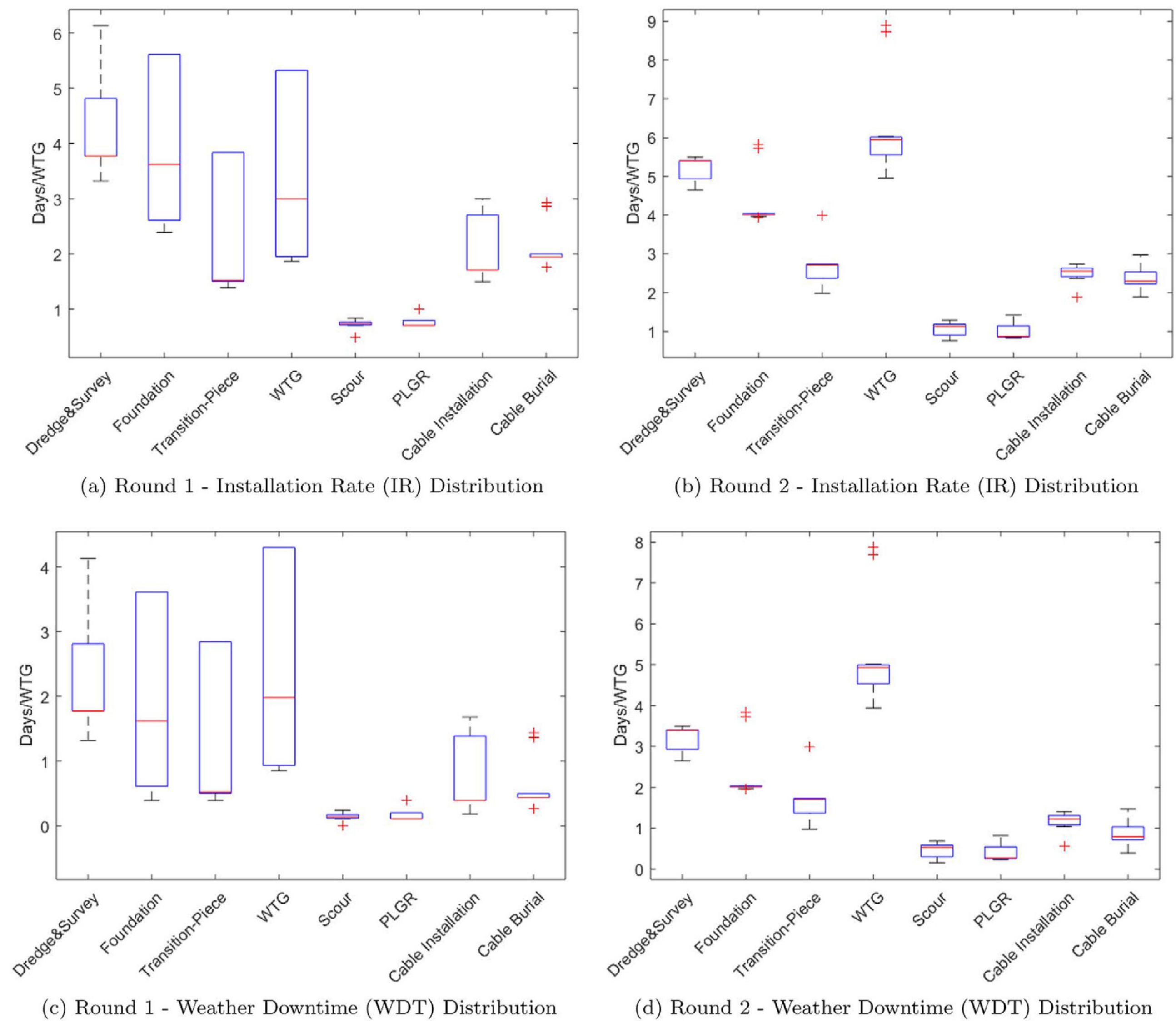

Fig. 4.3. (a) Round 1 - Installation Rate (IR) Distribution, (b) Round 2 - Installation Rate (IR) Distribution, (c) Round 1 - Weather Downtime (WDT) Distribution, (d) Round 2 - Weather Downtime (WDT) Distribution.

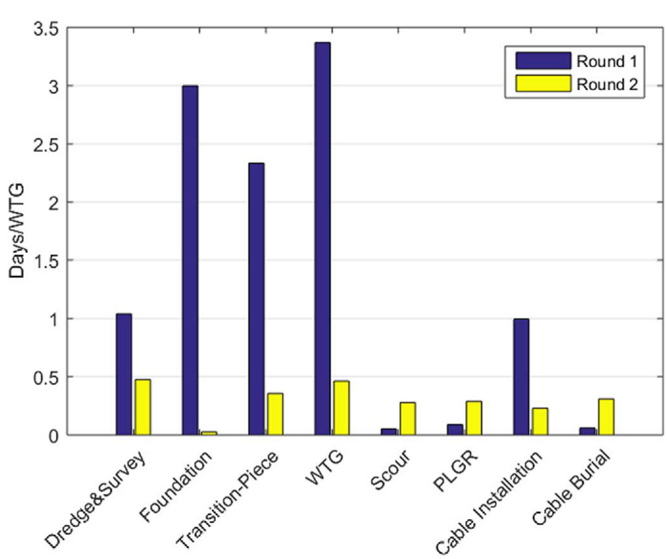

Fig. 5.1.2. Phase IQR Quantification: Rounds 1&2.

5. Discussion

The outcomes and reasoning surrounding the results is covered in this section. We begin with the Installation Rates and WDT values included in Figs. 4.1 and 4.2, which list the average result for the various scenarios within each installation phase, across the two rounds. The results used to draw these averages were compiled separately to allow analysis by rounds and review of the scenarios that resulted in the largest recorded durations.

5.1. Vessel performance by round

The most notable average results from each round is covered in the following sections and considers the source of these outcomes, including the contribution of each installation phase towards the averages obtained.

5.1.1. Round 1

In Round 1, the average total of construction days spent per wind turbine, which includes all phases across all scenarios, are the lowest for both rounds at 20.23 Days/WTG. This is complemented with a WDT figure of 10.21 Days/WTG on average and both exhibit a standard deviation of 3.2 Days/WTG. Despite the adoption of less dedicated and specialised vessels on the market, it appears that Round 1 sites benefit from their near shore locations. This characteristic provides more sheltered conditions during construction reduces the impact of weather on the vessels and subsequent delays. However, in Round 1 projects the averaged results suggest that over 50% of the charter time for the vessels would likely be attributed to downtime. The average combined construction duration was found to be 403 days, which required a total of 640 individual boat days relating to the overlap of phases described in Section 3.6. These outcomes arrived at approximate weather downtime value of 328 days per project on average.

A review of the individual phases revealed that the Wind Turbine Installation phase makes the largest contribution to downtime recorded at 26%. The case which caused the largest impact in terms of IR and WDT was the mean case at 23.6 Days/WTG for IR and 13.6 Days/WTG for WDT. These were closely followed by very similar results for the distance to shore, inter-turbine distance cases at around 23–24 Days/WTG IR and 13–14 Days/WTG WDT. The lowest predicted duration was seen with the lower number of turbines scenario at 16 Days/WTG and 6 Days/WTG for IR and WDT respectively. It was expected that the maximum distance to shore and number of turbine cases would result in greatest recorded IRs and WDTs. However as the number of turbines or distances in the model increase, so does the elapsed time for each phase and delays gradually shift the start date of successive phases. This suggests that seasonal conditions can be incurred at different moments, during different phases of an installation campaign, stemming from the size of the project to be completed. For example the start date recorded for WTG installation in the case with the minimum number of turbines was 11/08/2017, whilst the start date for the maximum number of turbine cases was 12/05/2018. Despite this dramatic shift due to the size of project, the start date for maximum number of turbine case, is in May. It is likely that the weather conditions were more favourable in May than in August. This observation is further exemplified by the results for the start date cases, which have the same characteristics as the mean case but with a different date defined for the launch of the first phase. The results recorded for the upper start date case (starting: 01/04/2017) are the second lowest recorded at 16.8 days/WTG for IR and 6.8 days/WTG for WDT. It is also suggested that the weather downtime will increase if the vessel employed for each installation phase, has to return to base to reload various components, as is the case for the Foundation, Transition Piece and WTG vessels in this study.

Referring to the box plots in Figs. 4.3a and c, it is evident that many of the phases are quite variable in terms of IR and WDT with the largest spread of values observed for the Foundation, Transition Piece and Wind Turbine Installation. The large variation shown in Fig. 5.1.2 signifies a lack of consistency in the IR and WDT values for each scenario and indicate a significant amount of installation risk that could be expected for these phases throughout Round 1. This suggests that the vessels employed for these three phases at the time of Round 1, were susceptible to variations in their working climate, exemplified by the broad spread of values for the phases described above.

5.1.2. Round 2

Round 2 vessels are predicted to have the largest average IRs and WDT values between the two rounds. The average IR across all scenarios is 25.4 Days/WTG and 15.4 Days/WTG for the average WDT with a standard deviation of 2.17 days for both. This deviation is lower than Round 1 and it can be said that the installation risk is lower with the Round 2 vessels overall. The average WDT value represents an increase of 50% compared to Round 1. These initial outcomes convey the impact of more challenging offshore conditions typically experienced at these sites. The results indicate that on average over 60% of the entire vessel charter period would experience weather downtime, suggesting developers could have faced a significant bill for downtime for projects with similarities to this category. The average and combined construction duration was predicted to be around 1384 days per project, requiring a large number of separate boat days in excess of 2300 days combined. The average WDT value for all the scenarios in Round 2 was just over 1260 days per project.

Reference to the individual phases revealed that the WTG installation phase again made the largest contribution to overall WDT recorded at nearly 34% of all downtime on average, which is a considerable increase compared to Round 1. This implies that the typical turbine installation vessel employed during Round 2 was generally not ideally suited to the heightened weather conditions typical of more challenging waters further from shore. The scenario found to have the largest impact in IR and WDT was the lower number of wind turbines case with values of 29.67 Days/WTG and 19.62 Days/WTG respectively. The scenario with the least impact in the Round 2 predictions is the maximum start date (01/04/2017), with an IR of 23 Days/WTG and WDT value of approximately 13 days. This outcome is surprising as it may be expected that with less turbines, the installation rates may be better or at least stay the same. It is noted that for larger wind farms that the weather delays are averaged across a greater number of turbines, which may compensate the WDT predictions. It is again proposed, that the impact of successive scheduling can dramatically change the amount of downtime experienced, relating to the changing seasonal weather conditions. As there are less turbines in the minimum WTG case, this means phases such as the WTG installation, would be reached sooner and could be completed in more severe weather conditions, in comparison to larger projects that may not reach the most susceptible phases until a calmer weather season is incurred. To exemplify, the WTG installation start date for the case with the minimum number of turbines was recorded as 11/11/2017 and for the maximum start date case as 01/06/2018. It is again likely the weather was less severe in June than in November. It therefore suggested that a consecutive installation schedule as applied in this study, may not be the optimum approach when planning offshore wind farm construction.

It is apparent that the majority of phases experienced an increase in WDT on average and again the WTG installation phase has shown a 97% increase in average downtime in comparison to Round 1. Notably, the Scour Protection conveys a 250% increase, a 100% increase in PLGR, 58% for cable installation and approximately 40–45% increase for the Dredging and Cable Burial Phases. Two WDTs found to increase slightly are the Foundation and Transition Piece installation each confirming an approximate increase of 8% and 13% respectively on average. It is proposed that the vessels in Round 2 were not well suited to the conditions associated with these sites, which relates to the vessel types commonly chartered at this time. It is proposed that vessel availability restrictions are demonstrated in Round 2, as over-sized and weather sensitive heavy lift vessels were commonly employed. These vessels were used for phases such as foundation or transition piece installations and originated from other offshore industries, matched with inflated daily charter rates. It would be appropriate to apply a cost benefit analysis when considering the charter of these vessels in comparison to the resulting WDT costs that may be expected from more capable but less available vessels in the market. In some cases developers may have struggled to source a cheaper alternative with the improved capabilities and to some extent, this demonstrates that optimum vessel designs were not available or had yet to be built during the construction of Round 2 sites. Thus focus on the development of dedicated wind farm installation vessels was essential to the industry at this time.

The box plots in Figs. 4.3b and d show significantly less variation in comparison to Round 1. This suggests that despite an overall increase in WDT on average, the vessels employed for Round 2 performed more consistently and therefore a reduction in the installation risk is observed in Fig. 5.1.2. This means more certainty could be drawn from WDT predictions but the challenge in reducing the overall magnitude of these delays was still a concern. The Scour Protection and PLGR phases still exhibit fairly low IR and WDT values compared to Round 1 but the plots demonstrate more variability in the results, which suggests these vessels may perform less consistently when used in more challenging conditions.

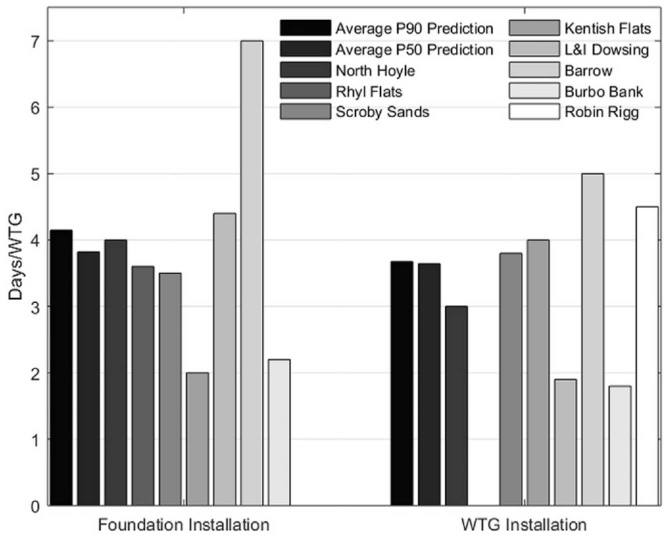

Fig. 5.2. Average Prediction vs. Recorded Installation Rates - Round 1 (Kaiser and Snyder, 2012).

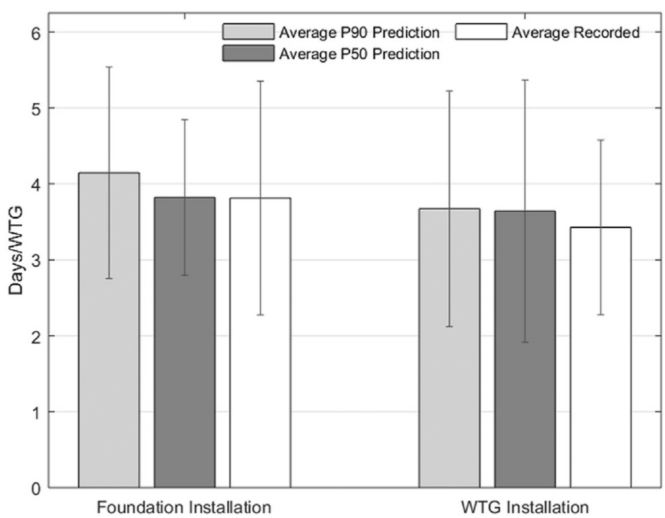

Fig. 5.3. Average Prediction vs Average Recorded Installation Rates - Round 1 [± 1 S.D.].

5.2. Value to planning personnel

The presented approach is of interest to planning personnel, as a structured method to identify and benchmark offshore wind installation risks. Whilst the study and simulation do not relate to any specific project, it has provided a basis to schedule vessel missions based on the bounds of the two installation rounds.

Ensuring efficient, low cost installation strategies is essential if offshore wind is to make a meaningful, cost effective contribution to the UK's energy mix, aiming for a levelised cost under £100/MWh (The Crown Estate, 2012). Many of the delays identified have been tackled by introducing innovative vessel designs, made to cope with more extreme weather conditions and increased deck space or lifting capabilities. This paper has assessed the environmental capabilities of the vessels and attempts identify their susceptibility to various project characteristics, to help reduce the costs of this industry and offer guidance on vessel charter.

As the study has been compartmentalised by UK offshore wind rounds 1 and 2, it is intended that operatives can benchmark these findings against the outcome of their own projects and compare vessel performance predictions. This study provides a clear indication of the installation risks for the vessel spreads used in each round and the phases predicted to have the largest installation risk, highlight areas where precautionary or mitigation steps may be required when chartering vessels with similar capabilities.

A method to approximate the WDT for each installation phase is discussed in Section 4.1. It is demonstrated that the selection of the vessels identified in Round 1 for a site of this category, would generally result in lower weather downtimes but there may be significant variation in the Foundation, Transition Piece and Turbine installation phases. The vessels specified for Round 2 exhibit considerably less variation but larger weather downtimes compared to Round 1. This result proposes that more modern vessels should perform more consistently. Management could take more certainty on their predicted WDT figures, if they opt for and can access the most sophisticated vessels available. It is also found that periodic scheduling of installation phases should be considered when conducting an offshore wind development. The consecutive nature of the phases employed within this study has revealed that the larger, less accessible projects may not experience the greatest downtime as a result of shifted schedules from delays incurred during earlier phases.

We have demonstrated the effect of successive scheduling of installation phases in these type of models, as delays incurred earlier in the project can shift the start date of phases waiting to begin. It is therefore suggested that individual models are primarily constructed for each installation phase, with a preferable or predicted start date. The effects of different start dates could be assessed by the individual models and would aid planners in the construction of a master installation schedule, compromising between the impact of delays and preferred installation periods.

To generalise these perspectives, Round 1 vessel technology exhibits the lowest WDT although a considerable amount of variation in the observed delays may occur if employed for more remote, unsheltered locations. The vessels employed for Round 2 offer more certainty as the results appear more consistent but are predicted to experience larger WDTs. This demonstrated that despite the adoption of a more standardised approach for these projects, there was an opportunity to reduce the WDT figures with more sophisticated and capable vessels.

5.3. Data validation

The IRs presented in Kaiser and Snyder (2012) were used to complete a validation of the adopted method and analyses. Within this reference, the Kaiser et. al list observed IRs (Days/WTG) for foundations and wind turbines from eight UK Round 1 wind farms. These values are presented in a 'boat days' basis which represent the entire time spent per vessel for each foundation and turbine installation in days/WTG. This metric provides a suitable base for comparison and, as these phases were predicted to have some of largest weather downtimes in Fig. 4.2, it should provide an interesting reference. Unfortunately, the authors are unaware of any other available data set that presents the remaining installation phases in this manner. P50 predictions were also computed during the simulations completed for this study and the P50 IRs were obtained using the same approach in Section 4. The average P90 and P50 prediction for the Foundation and WTG phases, are compared against the average IRs recorded across various Round 1 sites in Fig. 5.2. An initial review of the data demonstrates that the Average Round 1 predictions, both P90 and P50, are of similar order to the recorded values for the Round 1 site. This gives an indication that the predictions produced by the software and the method to obtain the IRs, can produce realistic results.

The average predicted and recorded IRs for the Foundation and Turbine installation phases are compared in Fig. 5.3. The error bars signify± one standard deviation and represent the variation in the results. It is evident in the average P50 prediction is nearly identical to the recorded IRs for the foundations at 3.8 days/WTG. The P90 results are on average greater than the P50 and recorded IRs at approximately 4.1 days/WTG, but are similar to the P50 values in the WTG installation phase at 3.7 days/WTG, compared to 3.4 days/WTG for the recorded data. The error bars show a considerable spread for the data in both the P50 and P90 predictions. It can therefore be deduced that as the recorded average lies within the error bar of the P50 and P90 values, the values show similarity to the recorded data, providing further confidence in the predicted results.

The error bars for the Pxx values are much broader in the WTG data when compared to the recorded IRs and the P50 error bar has a smaller spread against the other two values for the foundation data. This indicates that these probabilistic results produced by the software, can over and under predict the average IRs in specific cases. The average P50 values are closer to the recorded IRs and are only 6% greater in the WTG category. As the P90 outcomes were selected to represent the upper bounds of the software predictions, it was expected these values would be greater than the recorded IRs, yet these show good agreement with the recorded data. The P90 predictions are approximately 10% greater than the recorded IRs on average and demonstrate this approach can be used to produce conservative estimates.

5.4. Limitations and future work

This paper aimed to model the scenarios, vessel spreads and offshore wind farm characteristics using an offshore wind installation software. As the analysis progressed it was clear a few amendments to the modelling approach may have produced a more comprehensive set of results and offered more insight in the progression of the marine operations throughout the various scenarios and rounds.

Firstly, it should be noted that all of the results presented are taken from P90 predictions from the software. This implies that the predictions are somewhat pessimistic in their outlook offering 90% certainty that the values will not be exceeded. It may be the case that these results do not resemble what will occur in reality, although this metric does provide a good level of confidence that observed durations will be within bounds of recorded predictions. It can be argued that the metric of 'average number of days spent per WTG' (hrs/WTG) may not be the most suitable way of depicting the IR of cable sections or burial operations but was identified to be the most applicable approach for use within the software tool. The cable lay and burial durations were obtained using reference to in-house planning documentation, and an average installation rate was obtained by dividing the total duration by the number of turbines for the particular project.

In each of the simulated cases, the same environmental limits are assumed for the installation tasks in both rounds. However with improved vessel capabilities, it is possible that the limits for the installation tasks could be extended. More modern, capable vessels may improve attributes such as stability and lifting capacity, beyond the transit and station keeping limits considered in this study. As such, different environmental limits could be allocated to each round and method statements produced by installation contractors could be used to obtain variable inputs for these parameters, subject to the vessel and equipment employed for installation. Furthermore, the impact of water depth is not considered in this study. The task durations could have been altered to account for this, by again consulting method statements or by applying an assumed α-factor. In many cases, an α-factor may be imposed by a marine warranty surveyor (MWS) to account for uncertainty in the forecast and/or applied as a contingency in the execution of the marine operations (Det Norske Veritas, 2011). The uncertainty relating to water depth could be quantified for various installation tasks and applied to obtain contingency durations It is assumed that the operational limits in this study (Table 3.4), are unconditional to an applied α-factor and the authors believe that the task durations are to the best of their knowledge, a fair representation of the values used in reality.

The main environmental limits that were considered for the vessels and operations in this analysis were predominantly focused on wave height and wind speed. Vessel transit speeds were also included to reflect the expected travel durations. The software can also account for the minimum wave period (s) and current speeds (m/s) however due to the lack of available data for operations and vessels, the parameters were not used. It would be more informative and would allow greater accuracy if these parameters were considered, which would rely on input from vessel owners and experience professionals in the field.

Additionally, it is assumed throughout that all vessels are capable of remaining offshore for the entire installation campaign (i.e. for the entire set of WTGs to be installed), with the exception of those for the Foundation, Transition Piece and WTG phases, set at a maximum of three phases per voyage. This was selected as the number of inward and outward transits required for the remaining vessels is considerably variable in reality. It is fair to suggest, if the remaining vessels were allocated with a maximum number of phases per voyage, a change in WDT be observed for these installation phases. The vessels have specified waiting conditions in the software and when these are exceeded, the vessel returns to shore. This means that these vessels did not remain offshore during bad weather and it is suggested that portion of the WDT calculated for these phases, will account for the time to transit to and from port. It should be noted that a weather window is not sought for a vessel's outward or inter-turbine voyages in the software. In some instances a vessel may partially cover the distance of a voyage and is required to return to port when the weather exceeds transit limits. This is a limitation of the software, as a forecasting mechanism similar to weather forecasts issued in reality, could be built into the software to prevent the likelihood of unsuccessful voyages and improve the authenticity of the results.

For the modelling of WTG installation in the software, it was assumed that the associated duration was based on the 'bunny-ear' installation configuration. It is of the author's interests to extent this study, considering impact variable WTG installation strategies as presented in Kaiser and Snyder (2012) and Maples et al. (2013). It is noted that the sequence of the installation phases considered, is not standard to all offshore wind installation projects. The analysis completed is not wholly dependent on this sequence but if this was altered, the results for each phase could change, as these would begin at different periods in the simulated weather scenarios. However, as various knock-on delays are incurred as a result of the consecutive scheduling approach, the phases are applied at various months and seasons throughout the simulation.

As with many meteorological data sets, a number of missing entries were discovered and as the tool is reliant on evenly spaced intervals when forecasting the weather, linear interpolation was applied to compensate for these missing entries. This inevitably introduces a degree of approximation within the weather forecasting that may have altered the results slightly and a complete set of entries would provide further confidence with the results.

The software implements suspension to the marine operations between specified sequences if the vessel is able to hold station offshore. However in the interests of modelling time, only one sequence was specified within each installation phase that encompassed the entire duration of all the sub-tasks. If the phases had been modelled with multiple embedded sequences this may have provided a higher resolution in the results and adjusted the WDT predictions. As each of the phases across all the models only consisted of one sequence, it is fair to presume the simulations were completed on a level basis and can be used for comparison in terms of overall vessel performance. It is not advised that the predicted IRs or WDT values are used as a direct reference and should only serve as reference or sense check for similar analyses. The results used to formulate the IRs and WDT values are initially taken from the calendar outputs produced by the software. These outputs are presented in the form of dates and each completion date for the phases, is a result of the duration rounded to the nearest day. This indicates that the results are likely to over or under predict the phase durations but are believed to provide a good level of approximation for comparison.

Modelling and investigation on the impact of learning rates observed by Kaiser and Snyder (2012), is of interest to the authors. This can be modelled in the software tool and presents an intriguing expansion for this study. A review on the associated costs for the WDT predictions against charter rates of the vessels, would provide a helpful means to assess potential trade offs when employing particular vessels and sub-contractors.

6. Conclusion

This paper presents the application of an offshore wind farm installation simulation tool to assess the performance of vessel technology employed across offshore wind development Rounds 1 and 2 in the UK. The study provides a retrospective analysis on the expected performance of the vessel types employed and describes a structured method to identify and benchmark offshore wind installation risks

We have presented the fundamental architecture and functionality of the software tool, stipulating the application of Monte Carlo simulation in conjunction with embedded forecasting and logistical models that play out the operations across a set of stochastic weather scenarios. A description of the HMM used to generate weather scenarios is provided. We have explained the use of P90 exceedance probabilities in our results and the post-analysis used to determine installation rates (IRs) and weather downtime (WDT) values in days per wind turbine (Days/WTG) or turbine location.

Two meteorological data sets were used and sourced form recorded and modelled data, each were selected to resemble the conditions of a Round 1 and 2 site in turn. The variable wind farm characteristics considered within both rounds are presented in Tables 3.1, 3.2. In total 11 different scenarios were simulated for each round to gauge vessel performance. We completed a review of the available information to ascertain the most commonly used vessel for each installation phase within the rounds. A comprehensive description on the application of these vessels and the assumed installation strategies, is also presented before arriving at our selected vessel spreads in Table 3.3, which we believe to resemble the most commonly chartered vessel types in both rounds.

The operational limits and durations of the installation phases are presented in Section 3.6, which dictate the wave heights and wind speeds that must be satisfied for the work to be completed at site. We have proposed alteration of the task values in future analyses, to account for the logistical capabilities of the vessel types investigated. The influence of vessel performance is based on transit and survival limits, which dictate the transit progression, duration, station keeping and navigation to the next turbine location.

The results indicate that the lowest IRs and WDTs are associated with Round 1, which can be justified by the sheltered near-shore location of these sites, meaning the vessels were protected from severe weather conditions expected at Rounds 2 sites. This is affirmed with the results for Round 2 which exhibits the largest IRs and WDT values and is believed to demonstrate the limitations of the vessels employed for these installations.

The box plots presented in Figs. 4.3a– d have highlighted that Round 1 vessels experienced lower levels of WDT with potential for variability, exhibiting uncertainty in the predicted downtimes. For Round 2 the variability is reduced but the WDT increases overall, showing the vessels would perform more consistently but the delays experienced may be prohibitive towards the cost of each project. The quantification of IQRs in the results for the two rounds, has provided a view of the installation risk associated with the representative vessel spreads and highlights where precautionary strategies may be best applied to overcome costly delays. The limitations of the software, model construction and overall methodology, has been discussed in Section 5.4. We have found the IR results for the foundation and WTG installation phases in Round 1, compare well with the IRs recorded at a range of Round 1 projects.

It is noted that when consecutive installation sequence is adopted, start dates can be delayed and the knock-on effect can induce significant downtimes in successive phases. It is therefore suggested that future work could consider methodical analysis and scheduling to devise a robust master plan for an entire installation project, accounting for seasonal weather conditions. Additionally, we foresee expansion in the fragmentation of installation sequences to assess the impact of suspendability during the operations. Lastly, the authors are interested in the cost trade-offs between the predicted WDTs and vessel charter costs, to support planning and contracting processes.

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2. The Crown Estate - The Marine Data Exchange: http://www.marinedataexchange.co.uk/

Appendix A. Annexe

See Table A.1.

Table A.1
Assumed vessel characteristics.

Vessel	Round	Transit Speed Loaded (kn)	Transit Speed Unloaded (kn)	Transit Conditions		Waiting Conditions	
				Max. Wind Speed (m/s)	Max. Wave Height (m)	Max. Wind Speed (m/s)	Max. Wave Height (m)
Injection Dredger	1	10	11.2	12	1.2	15	1.8
WTIV	1	11	12.1	15.3	2.8	36.1	10
WTIV	1	11	12.1	15.3	2.8	36.1	10
Jack-up Barge	1	10	11.5	10	1.5	15	2
Rock Dump	1	6.5	8	10	1.5	15	1.8
Multicat	1	10.8	12	10	1.8	15	2
Barge	1	6	8	10	1	12	1.5
MPSV	1	7	7.7	12	2	15	2.5
TSHD	2	10	11.3	15	2	20	2.5
Heavy Lift Vessel	2	9	12	15	1.8	20	3
Floating Crane	2	2.8	7	15	2.5	20	3
WTIV	2	11	12.1	15.3	2.8	36.1	10
Fall Pipe Vessel	2	11	12	15	2	20	2.2
Offshore Vessel	2	6	8.5	10	1.2	15	1.7
CLV	2	7	9	15	1.5	20	2.8
MPSV	2	12.5	16	15	1.5	20	3

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