On using simulation to model the installation process logistics for an offshore wind farm

Abstract

The development of offshore wind farms (OWFs) in Europe is progressing to sites which are characteristically further from shore, in deeper waters, and of larger scale than previous sites. A consequence of moving further offshore is that installation operations are subject to harsher weather conditions, resulting in increased uncertainty in relation to the cost and duration of any operations. Assessing the comparative risks associated with different installation scenarios and identifying the best course of action is therefore a crucial problem for decision makers. Motivated by collaboration with industry partners, we present a detailed definition of the OWF installation process logistics problem, where aspects of fleet sizing, composition, and vessel scheduling are present. This article illustrates the use of simulation models to improve the understanding of the risks associated with logistical installation decisions. The developed tool employs a realistic model of the installation operations and enables the effect of any logistical decision to be investigated. A case study of an offshore wind farm installation project is presented in order to explore the impact of key logistical decisions on the cost and duration of the installation, and demonstrates that savings of up to 50% can be achieved through vessel optimization.

Keywords: simulation, scheduling and logistics, renewable energy, maritime industry

1 Introduction

1.1 Problem context and background

The installed capacity of offshore wind energy has steadily increased in Europe over the last five to ten years and is predicted to continue increasing over the coming years [16]. To meet **the learning effect parameter has time dependent prob... so not so sure what is fixed at time 0.... i guess its the initial prob p_3 and the learning function - in fact i think we are assuming a fixed learnign function ... or do we "learn" about the learning function?** current targets OWF developments are progressing to larger sites located further from shore in deeper waters [16], which gives rise to new challenges. These sites are exposed to more severe weather conditions than more coastal sites, increasing the complexity of offshore operations and the uncertainty around planning and managing these operations. In particular, the process of installing an OWF is susceptible to these challenges, and installation and logistics have been identified as areas where substantial cost-reductions can be achieved through innovation [29, 1]. In this setting, two possible mechanisms for supporting innovation are: an improved understanding of the impact of logistical decisions to enable validation and comparison of novel installation strategies and concepts, and an improved understanding of the economic impact of vessel capabilities on a particular installation schedule, enabling novel vessel designs to be validated and developments in vessel capability to be directed such that profits are maximised for both OWF developers and installation contractors. The offshore wind industry is under increased pressure to reduce costs in order to improve competitiveness with other energy sources [31], and recent estimates give the installation costs as 19% of the total capital expenditure, or approximately £0.7M/MW [1]. Enabling these innovation mechanisms therefore has the potential to develop the competitiveness of the industry.

1.2 General framework of a maritime logistics problem for an offshore wind farm installation project

OWF installation projects will typically consider various asset-types, with a large number of each type of asset to be installed. The most recognisable assets are the wind turbine generators (WTGs), which are built on top of subsea foundation structures. Offshore substation platforms (OSPs) may be included to collect and/or convert the generated power for transmission to the onshore grid. The most viable option currently available for foundations are pile-driven jackets, which are large metal lattice structures secured to the seabed with metal piles. The WTGs are connected to the OSPs via inter-array cables, and the OSPs are connected to the onshore grid via export cables. A detailed description of each type of asset and an overview of the different stages of the OWF installation process can be found in [15].

Each asset-type is associated with a specific set of installation operations that are typically repeated many times. Additionally, there are a number of support operations associated with each asset-type, which prepare or complete the asset installation process. Together, these give a large set of distinct repeated operations which must be completed. Each individual operation has specific operational limits including daylight and weather restrictions, which are dependent on the operation and the particular vessel used. Multiple vessels and multiple installation techniques may be used to install each type of asset, with each vessel having unique operational capabilities and capacities. The expected duration of each task is dependent on the particular installation vessel used for the task, and the task duration realised in practice is subject to uncertain weather conditions. Installation vessels may be used for the installation of multiple asset-types and some asset installations may be supported by supply barges. Further to vessel logistics, each type of asset may be loaded from a separate port and each port will have specific operational capabilities and capacities. Assessing the comparative benefits of different logistical decisions – in terms of the impact on the length of the installation process and the net costs – over an entire OWF installation project is therefore challenging, and the large scale of these developments amplifies the impact of any operational decisions as these are carried-out many times across the OWF site.

The OWF installation process problem presented here contains aspects of various existing maritime logistics problems (see Christiansen *et al.*[8] for a recent review). Decisions on fleet size and composition will define how many installation vessels are employed for each category of asset installation as well as the specific vessels utilised, where each vessel will have unique operating characteristics. Decisions on vessel scheduling will determine how each vessel is used in terms of the order of assets installed, start-dates for use, and any periods of unavailability. Decisions on the ports used for loading each asset will influence the installation operations through loading times, loading unavailability and transit times between the port and the OWF site. The impact of each of these decisions is modelled over the installation-horizon subject to uncertain weather conditions. Additionally, this problem is uniquely characterised by the complexity of modelling a large number of operations which are subject to unique operational limits with stochastic weather conditions.

The challenges in modelling this problem are largely driven by the requirement of practitioners to have sufficient accuracy and usability to support decision making on these vast installation projects, with costs spanning to hundreds of millions of GBP. Each stage of the installation process must therefore be modelled with sufficient accuracy to be sensitive to the potential differences related to the various aspects of the problem outlined above. In addition to accurately representing the logical relationships between the different vessels and supporting operations (which could typically number over 50), particular challenges include accurate modelling of: (i) the uncertain weather conditions, (ii) the uncertain task durations given favourable weather conditions, (iii) vessel failures and maintenance, (iv) operations which can be completed in stages, (v) operations which may require weather windows longer than the expected duration for safety reasons, (vi) the installation of different asset-types using a single port with limited loading capacity (which prohibits the installation of the different asset-types from being modelled compartmentally), (vii) groups of operations which may require installation within the same weather window, and (viii) the various ways in which a vessel can be supported by supply barges.

1.3 Existing literature

There are relatively few studies on the logistics of installing an OWF, and existing studies typically consider subproblems of the problem framework outlined in Section 1.2. These studies can be categorised as simulation approaches and optimisation approaches.

1.3.1 Simulation-based OWF installation logistics studies

In Lutjen and Karimi [24], a two-level discrete event simulation which couples a port inventory control system with a reactive scheduling component is used to determine the effect that different levels of inventory have on the progress of the installation process. A relatively simplistic model of the installation process is used, considering only a single vessel for the installation of the turbines and their foundations, and with six operations used to entirely describe these activities. Lange *et al.*[22] present a simulation tool which models the construction of an OWF from the manufacturing of components through to final installation, providing a high-level view of the entire installation process which can identify key stages in the manufacture and supply network that could lead to potential bottlenecks. The tool has some flexibility regarding high-level installation process decisions, such as alternative installation strategies and the optional use of supply barges; however, the focus of their tool is to support decisions related directly to the supply chain, and as such the presented modelling of offshore operations is relatively simplistic. Stempinski *et al.*[37] consider the scheduling of installation operations for tripod turbine foundations. The main focus of their paper is a detailed engineering investigation of this operation, in order to accurately parameterise the limiting weather conditions which are used to simulate the installation. The installation schedule is limited to the pre-determined schedule of a single installation task (installing tripod foundations) with a single installation vessel. Recently, Muhabie *et al.*[27] present a high-level discrete-event simulation model for OWF installation, with only 10 different operations used to entirely model the installation of turbines and foundations. The model appears to consider three installation vessels (each installing one type of asset), supported by a supply barge which has transits modelled as having no duration or weather limits. Morandeau *et al.*[26] present a general purpose simulation-based tool to model the progress of offshore operations to install marine energy sites. Their tool, referred to as Mermaid, is demonstrated for the installation of 10 tidal energy arrays using a single installation vessel in four phases of sequential operations (related to piles, foundations, turbines and cables), although could also be applied to the installation of OWFs. Little information is provided, however, on the modelling approach to these operations, and the flexibility and accuracy with which this tool could be expected to model a large-scale OWF installation project as presented in Section 1.2. It should be noted that since publication of their paper, the Mermaid tool has been released commercially [25].

Various approaches are taken to model the uncertain weather conditions in these studies. A deterministic approach is presented in [24] which assigns appropriate vessel loads and operations using forecast weather conditions, with five categorical weather states considered; however, this is reliant on accurate forecasts, and five weather states would not be sufficient to model the full range of weather restrictions which would be required. In [22] successive weather states in time are modelled using Markov chains; however, this approach would potentially increase the uncertainty of the model. For example, generating realistic weather conditions which accurately capture aspects such as seasonality, correlation between wind and wave conditions, and the fluctuation of conditions throughout a day would require the specification of various probabilities which would be difficult to define, and as a result accurately modelling the sequential completion of a series of offshore tasks with different weather limits would be challenging. A probabilistic assessment of weather downtime is used in [37] to scale the expected duration of each task and generate the total schedule duration, which is recognised by the authors to provide an optimistic duration due to the capability of this approach at handling the sequential completion of a series of offshore tasks with different weather limits. This deficiency is addressed in [27] by incorporating conditional probabilities to model the completion rate of successive tasks with greater accuracy; however, in practice every vessel operates by completing extended sequences of successive tasks, and developing accurate conditional probabilities to model this behaviour would be challenging. Several of these studies also model the uncertain weather conditions using a time-series model based on historical weather data (see [37, 27, 26]). Whilst conceptually similar to our approach, this method is limited to the number of years of recorded weather data available, and as such would be unlikely to represent the true probabilistic range of weather conditions which could realistically be expected in a given year.

Based on the information available in these studies, it is our opinion that neither the level of fidelity available with these methods to model the installation process, nor the robustness with which the uncertain weather conditions can be modelled, would be capable of providing the level of accuracy which would be required by developers to support the high-cost installation of an OWF.

1.3.2 Optimisation-based OWF installation logistics studies

Optimisation-based approaches focus specifically on the scheduling of installation vessels. The most recent and detailed study is of Irawan *et al.*[19], where a bi-objective optimisation model minimises the cost and duration of the installation process with three types of asset (substructure, turbine topside, and inter-array cables). The authors propose an exact solution approach with compromise programming and a metaheuristic approach, and computationally test these on problems with up to 120 turbines and 10 installation vessels, a realistic size for the problem outlined in Section 1.2. However, substantial simplifications of the installation process are used in the paper, including but not limited to assuming sequential operations for all vessels, deterministically handling daily weather forecasts, and allowing on-demand hires of vessels (when in practice most vessel contracts are agreed far in advance). In earlier studies, Scholz-Reiter *et al.*[33] and Ait-Alla *et al.*[2] propose mixed-integer programming models for short-term vessel scheduling, considering small-scale problems with up to 10 installation operations, 30 turbines, 3 installation vessels, and 3 scenarios. In comparison, the scheduling aspects of the problem outlined in Section 1.2 are substantially more complex, and hence it is unlikely that these approaches would scale effectively to real-world problems. All three papers represent weather data in categorical states, supplied to the models as deterministic inputs.

1.3.3 Positioning the OWF installation logistics problem within wider literature

In a more general context, two areas of maritime logistics research which have some degree of similarity with the OWF installation logistics problem outlined in Section 1.2, are problems related to OWF operations and maintenance (O&M) logistics, and problems concerning offshore support vessels (OSVs) for the oil and gas (O&G) industry.

In comparison with the OWF installation logistics problem, O&M logistics problems for OWFs have received considerably more attention in the literature. As with the installation problem, both simulation and optimisation approaches have been proposed to tackle the O&M problem, and Shafiee [34] provides a recent overview of the O&M logistics problems for OWFs and the approaches which have been considered to-date. There are similarities between the OWF logistics problems for installation and O&M, particularly with respect to fleet-sizing and fleet-composition considerations, as in each case a number of tasks with different operating restrictions must be completed subject to uncertain weather conditions, and these tasks may be completed by different vessels. There are key differences for the O&M problems, however, in that the required tasks are determined by asset failures which occur randomly throughout an OWF site, that the number of different maintenance tasks which may be required is relatively small (particularly from a vessel scheduling perspective), and that there is unlikely to be any precedence relationships between a given pair of O&M tasks, so that each task could potentially be completed independently from the other. As a result, the nature of the O&M scheduling problem is very different to the scheduling aspects of the OWF installation logistics problem.

In their latest review of the ship routing and scheduling literature, Christiansen *et al.*[8] include a review of the small number of studies concerning OSVs for the O&G industry. More traditional maritime routing and scheduling problems typically require that one or more vessels transit between locations, where each transit is completed subject to specific weather restrictions, and weather conditions are stochastic in nature. The O&G OSV problems increase the modelling complexity by considering different kinds of task (typically a transit task and an offshore operation) which must be completed subject to uncertain weather conditions, and where each type of task may have different operating restrictions. As with the O&M logistics problems for OWFs, the O&G OSV problems are therefore similar to the OWF installation logistics problem in that each problem requires that a sequence involving different tasks is completed at various locations subject to strict operational restrictions specific to each task, and different in that the O&G OSV problems typically consider a small number of different tasks and different operating restrictions, in comparison to the large number of different tasks which may comprise the OWF installation process.

1.4 Outline of this paper

The objective of this study is to design and develop a discrete-event simulation model of the OWF installation process as outlined in Section 1.4, in order to provide decision support to OWF developers at the planning or bidding phase of an installation project. This simulation model is purposefully designed to provide an accurate representation of the installation process, enabling alternative logistical installation decisions to be assessed and compared in terms of the expected duration of each phase of the installation process and the resulting impact on costs, such that the high-cost decisions related to the installation process can be supported. This tool has been fully developed and implemented in Matlab and is currently being used by our industry partners (see Section 5 for further information).

Utilising this simulation tool can provide OWF developers with an improved understanding of the uncertainties related to the cost and duration. This enables evaluation of a given installation scenario modelled over the entire planning-horizon, in addition to factors such as: the impact of changes to fleet size, fleet composition, vessel schedules, port selection and changes to installation costs including vessel, port and crew rates.

Simulation is widely used in practice as a methodological approach to operational research problems where the complexity of the problem structure, the input variables, the output variables, or the demands of the client are such that an analytic approach would be difficult to achieve (see for example [28, 38, 41]). In the OWF installation problem considered here, the number of operations which must be completed, the diversity of the operations considered, and the necessity to gain a realistic understanding of the impact of uncertain weather conditions, task durations and vessel failures each contribute to the complexity of the problem. Furthermore, the intention of this study is to provide a means to evaluate and compare the numerous logistical decisions considered during the planning of an OWF installation campaign. These decisions will represent the viable alternatives available for a given stage of the installation and the experience of the OWF developers. Given these considerations, a simulation approach is employed here.

The remainder of this paper is structured as follows: Section 2 outlines the OWF installation process model and Section 3 describes the simulation and weather models; these are employed to investigate the impact of logistical decisions for a case study OWF in Section 4, and discussion of a real-world application is provided in Section 5, with conclusions and areas for future development provided in Section 6.

2 Problem description and modelling considerations

2.1 Industrial setting

The installation process model used here was developed through close collaboration with experts from three companies with direct experience of the European OWF industry: SSE Renewables, Scottish Power Renewables and Technip Offshore Wind Limited. Each company provided at least two experts, whose job titles included, for example, Head of Installation and Logistics, and Head of Offshore Marine and Construction Engineering. The installation process model presented here is focused on the next phase of OWF developments, which will be located further from shore in deeper water than has previously been encountered. Furthermore, as these sites are to be developed in the near future the focus was on proven installation methods which would realistically be considered by a developer today, rather than immature techniques and technology which represent a higher risk. As such the model presented in detail below is representative of the current industry practices and experiences.

A series of workshops with the industrial collaborators were held to iteratively develop the installation process model. The development process largely followed the facilitated simulation modelling approach presented by Robinson *et al.*[32]. Developments to the model were proposed by the industry collaborators, and accepted or rejected following detailed discussions on the impact of these with respect to model accuracy and fidelity, coding implementation time, and computational run time. This iterative process defined all aspects of the model, including the model-scope, the level of detail required to model the various installation operations, and the number of weather parameters which would be considered in the model. The resulting model is therefore designed for and by practitioners to support the key decisions during an installation project.

2.2 Model scope

The installation model developed here is intended to cover all operations specifically related to the process of installing an OWF and is centred on the key assets identified in Section 1.2. For each asset the scope of the installation process model is focused on installation operations, and consideration is given to the natural, practical and contractual bounds to the installation which have been identified by industry experts and are outlined below. It is assumed that the manufacturer and model of each asset has been decided prior to the start of installation, and that the locations of each OSP and WT, the paths of all cables, and the location of onshore substations are all known prior to installation. Management of the asset supply-chains is considered to be outside the scope of this project; however, the supply rate of some assets is identified as an important consideration in modelling the installation. Each category of asset is therefore assigned a fixed arrival rate which takes all aspects of the supply chain into consideration and assets can only be installed or assembled after arrival.

Each asset installation is considered from the arrival of assets at port prior to final transit to the OWF site. Installation vessels are considered from mobilisation at the vessel base port through to demobilisation. The installation operations are defined to cover all operations until an asset can be considered as completely installed, and all installation operations culminate when the WTGs and OSPs go online.

Assumptions of the installation model include: the minimum time-step of the analysis is one hour, the distance between any two locations on-site is equal, the water depth at each on-site location is equal, and that perfect weather forecasting is possible such that a given weather window can be fully exploited as appropriate. Additional assumptions related to the installation operations, vessel and barge use, maintenance and costing are provided in Sections 2.3-2.5.

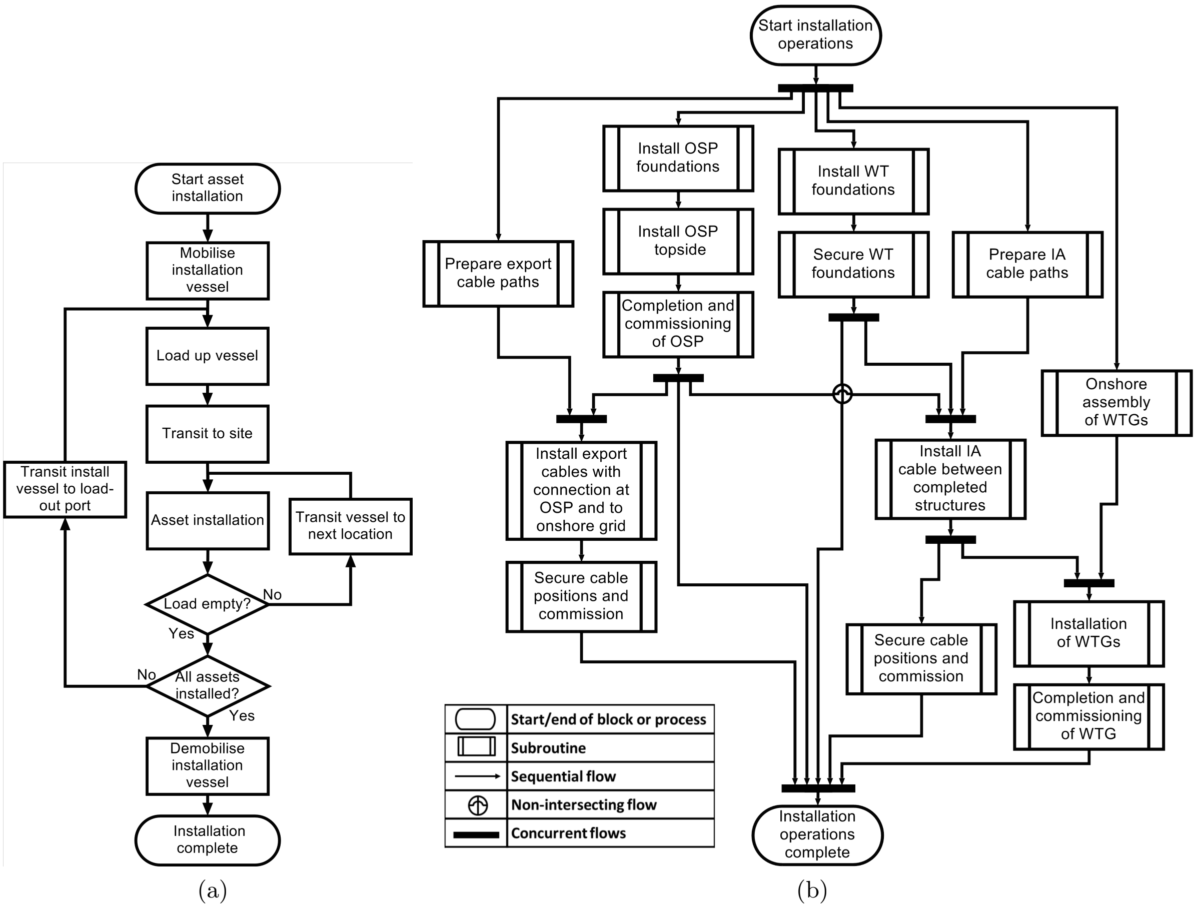


Figure 1: (a) Flowchart for a standard OWF asset installation process, and (b) High-level schematic of relationship between the different OWF asset category installation processes

2.3 Installation operations

The OWF installation process is partitioned into a number of installation operations, with each operation potentially comprising a number of smaller tasks. An installation operation is defined as a key stage of the installation process, and subsequent operations should be characterised by different operational limits or considerations.

The flowchart for a standard asset installation process is displayed in Figure 1a, and installation of each of the key assets follows a similar approach. Each installation operation is defined in terms of duration, weather and daylight restrictions, and in cases where the operation can be completed in stages the minimum weather window required for each stage is included. Even under perfect weather conditions there will be some natural variation in the duration of each installation operation. The triangle distribution has been recognised for many years as an appropriate probability distribution to model uncertain activity durations in project scheduling problems [40], and remains one of the standard methods used for this purpose in the OR literature (see for example [17, 18, 35]). This is the approach taken here, as only the minimum, mode and maximum durations are required, which are relatively straightforward to elicit from experts.

Installation operations must be completed in the required order at each location, and installation of each category of asset proceeds from an activation date, subject to the completion of preceding operations. Where multiple vessels install the same type of asset, each vessel may be designated a unique set of operations for installation. To reflect operations which may be closed down over winter months there is the option to define seasonal downtime.

An OWF installation process will adhere to a series of precedence relationships between the various categories of asset and within each category. Many of these relationships are standard for OWF installation projects and represent the logical order in which each asset is practically installed; these are displayed in Figure 1b. Each subroutine shown in Figure 1b represents several installation operations, as defined previously, and in several cases installation subroutines cover installation operations for multiple assets. The flow portrayed in Figure 1b defines the order in which operations must be completed for a single structure (WT, OSP or cable), and in reality all subroutines will be performed in parallel whilst preserving this order on each structure.

2.4 Installation vessels and support vessel spread

The model enables the installation process of each category of asset to be performed by one or two installation vessels. This is representative of the realistic choices available to a decision maker, with the use of three installation vessels considered to be impractical in a real-world installation project. Each installation vessel is uniquely defined in terms of operational capability – the time required to complete each task and the weather and daylight restrictions which would be associated with this, the cargo capacity and an average charter day-rate. An installation vessel is activated through its mobilisation date and will proceed to install all required assets subject to preceding operations, with transit between locations and reloading as presented in Figure 1a. Upon installation of the final asset, a vessel will transit back to port before beginning demobilisation operations. Installation vessels are assumed to be capable of remaining offshore indefinitely, with factors such as the replenishment of water and fuel assumed to be addressed opportunistically as required, without impacting on the installation schedule.

The installation of some assets can optionally be supported by supply barges, with any number of supply barges potentially utilised. For practical and safety considerations, supply barges can only be used for the installation of a specific subset of asset categories. Day-rates for supply barges include vessel and crew costs as well as the use of tugs. Supply barges can be used for the installation of multiple categories of asset if desired.

Unexpected vessel and equipment breakdowns can either be included explicitly through the probability of failure for each asset installation vessel and each supporting operation subroutine, or implicitly by defining a percentage increase to the expected duration of each installation operation. Additionally, pre-scheduled maintenance operations can be included by defining periods of vessel unavailability at the outset of the installation.

2.5 Modelling of cost and revenue

The installation costs are derived from a combination of the day-rates and mobilisation rates of all installation and support spread vessels used, all port costs and the costs of all installation technicians and vessel crews. All costs can be calculated directly from the installation durations. Vessel day-rates are highly volatile in practice; however, long-term vessel charters will typically agree fixed prices for the duration of the contract. As the model presented here is intended to support planning decisions, the uncertainty in vessel day-rates is not captured explicitly, and costs for each vessel are assumed to remain constant throughout the installation project. The capital expenditure on installation operations is offset by the rate at which WTs come online and begin to generate energy and produce revenue. It is imperative for an OWF developer to understand and exploit the expected relationship between expenditure and production over the period of the installation, with both factors dependent on the installation duration.

2.6 Model validation

The structure of the installation process model presented in Sections 2.2-2.5 was extensively validated through a series of workshops held after each stage of model development. Each industrial partner confirmed the logical structure and its applicability to existing and future OWF sites, and the varied experience of the collaborators ensures that the capability of the model supports the decision making requirements during an OWF installation project. Note that verification of the simulation model outputs is discussed in Section 3.2.2.

3 Methodology

3.1 Weather time-series modelling

As highlighted in Section 1.2, the diversity of installation operations included in the model of Section 2 requires a comprehensive representation of the weather uncertainties and their impact on the installation. Synthetic weather series are time series of weather conditions generated from statistical analysis of historical weather data sets. Weather data is routinely collected on an OWF site over several years prior to installation, as understanding the expected weather conditions is of fundamental importance in estimating the generating capability of a site. The method used here to generate synthetic weather time-series is a correlated autoregression model, which follows the approach taken by Dinwoodie and McMillan [11] for the simulation of OWF maintenance operations. The weather conditions taken into consideration here are significant wave height and wind speed, which were identified by the industry partners as the most influential factors on offshore operations. Additional factors such as wave period and current speed will only impact specific operations, and to maintain tractable computation times these are not currently modelled. Autoregression identifies the underlying trends as a data-set changes over time, and exploits these trends to predict future behaviour of the data-set. The existing historical data-set is analysed to define the extent of the dependency on previous data-points such that the closest fit to the existing data-set is produced. Future data-points are then generated iteratively using the same dependency relationships. Employing synthetic weather series requires more computational effort prior to running the simulation than would be required with a categorical weather model; however, these time-series provide a realistic assessment of the ability to meet operational limits for the required durations in a sequence of installation tasks.

Monte Carlo simulation is a widely used technique to quantify the propagation of uncertainty in complex systems, where the uncertainty in output parameters cannot be expressed in terms of analytical functions of the input parameter uncertainty (see [13] for a recent text on Monte Carlo methods and their applications). In particular, Monte Carlo simulations have been at the heart of numerical weather prediction since the 1950s, and remain a fundamental component of modern weather forecasting [5] and modelling of systems subject to uncertain weather conditions [3, 30, 39]. Monte Carlo simulation of the weather model is used to generate many realisations of synthetic weather time-series, each of which are statistically representative of the characteristic properties of the historical data set.

3.2 Simulation of the installation scenario

3.2.1 Discrete-event simulation model

The simulation model combines the logical model discussed in Section 2 with the synthetic weather time-series model discussed in Section 3.1. Discrete-event simulation is a natural approach to model the OWF installation process and is the method used here; see [6] for a recent text on discrete-event simulation, and [10, 14, 20] for recent applications to model engineering systems.

A multi-threaded discrete-event simulation model is developed to represent the OWF installation process. Each installation vessel, supply barge, and support operation is represented by a separate thread, and each thread of the simulation therefore models the progress of a unique sequence of operations. Threads may progress in parallel subject to various logical constraints defined through the installation model of Section 2; these logical constraints represent factors such as the practical order assets are installed in and the synchronisation of installation vessels and supply barges, where appropriate. Each thread maintains a clock which records the time transpired since the global start of the installation project. The state of the model represents the current clock for each thread, the current progress of the installation for each WTG, OSP, and cable location, the location of each vessel and barge, and the current number of assets carried by each vessel and barge.

The OWF installation is simulated through a series of distinct events, where each event represents a particular sequence of operations which are carried out by the same thread(s). Events are characterised as pre-installation operations, in-port installation vessel or barge operations, on-site installation vessel or barge operations, and post-installation operations, and the partial or full completion of each event results in some change to the state of the model. The first stage of the simulation completes the pre-installation operations for all assets, as these can be grouped according to asset-type and each group is then completed independently. The remainder of the simulation iteratively selects a thread associated with an installation vessel or barge and completes the relevant operations. Selection is determined through a priority queue, where the level of priority is determined from the time of the thread clock and the satisfaction of various constraints to ensure the logical structure of the installation model is adhered to. Furthermore, priority is given to earlier operations in the sequence displayed in Figure 1b and installation vessels are prioritised over supply barges, in order to reduce the computational burden of processing constraint violations. The particular sequence of operations completed in each iteration is dependent on the selected vessel or barge, its current location, current cargo, and the associated type of asset. Each port may be utilised by multiple vessels and barges installing multiple types of asset, and as each port has a maximum capacity of vessels or barges which can simultaneously be loaded, the available capacity of a port must be updated following each set of in-port operations. The priority queue selection process for threads is necessary as a result of this factor, as otherwise each thread could be progressed independently. Installation vessels supported by supply barges are removed from the global priority queue once they are on-site, and supply barges arriving on-site are synchronised with an installation vessel selected from a local priority queue consisting only of the installation vessels for the appropriate asset-type. Upon the completion of events characterised as on-site operations, a sequence of post-installation operations are triggered, dependent on the type of asset in question.

A particular installation scenario for an OWF generates a unique set of installation operations and the precedence relationships between these, in addition to the defined durations, operational limits and sequencing of the required installation operations. The rate of progress of each thread in the simulation model is then calculated for each synthetic weather series generated through the Monte Carlo simulations, subject to random vessel failures and uncertain task durations, with the minimum time-step of the analysis defined as one hour. A contingency-time factor can be included which increases the required duration of the weather window to complete a particular operation. The detailed breakdown of operations expressed through the model delivers an accurate assessment of the progress of each thread of the simulation, and taken over a large number of weather series the simulation tool is therefore capable of providing an accurate measure of how an OWF installation process may be expected to progress in practice.

3.2.2 Inputs and outputs of the simulation model

As the model presented in Section 2 provides a detailed representation of an OWF installation process it is necessary to populate the simulation model with a detailed description of the entire installation process. Inputs to the model should define expected durations, minimum operational durations and weather and daylight operational restrictions for each installation operation, with distinction between multiple installation vessel use and supply barge use as appropriate. Additional information required includes average day rates for vessels and staff, average increase in durations due to maintenance, carrying capacity of each installation vessel and barge, arrival rates for each category of asset and activation dates for installation operations related to each asset category.

The nature of the simulation tool enables a wide variety of outputs to be produced, with detailed analysis of many aspects of the installation process possible. The outputs will generally originate from probabilistic measures which are calculated from the data generated across all simulations.

Probabilistic performance measures which can be used to evaluate an installation scenario include the mean and maximum cost and duration of installation and corresponding magnitudes of any delays experienced during installation. Each of these measures can be calculated for the entire installation process or calculated for a single asset category. Additionally, these could be calculated for a specific category of asset installation operations, such as the operations performed by a particular installation vessel, to provide a detailed breakdown of operations. Delays are recorded as any time-periods where a particular category of asset installation operations cannot proceed due to an incomplete preceding operation, or due to inoperable weather or daylight conditions, or insufficient weather window length. Following the recommendations of the industry partners, additional outputs of the OWF installation scenario simulation include details on installation milestones such as first OSP activation, first WT activation and 10% of WTs activated, and the progress of each asset installation. These outputs are an important consideration to an OWF developer for two reasons: firstly, an active wind farm produces profits through electricity generation, and so the quicker a site is partially or completely online the more profitable the lifetime costs of the site will be; secondly, a given OWF may have pre-defined obligations which are designated by government as part of the planning-approval process. Targets such as the first date of exported power or the date of site completion must be satisfied or substantial fines are imposed, and it is therefore important to have an understanding of whether these obligations will be met.

Due to commercial sensitivity it has not been possible to publicly verify the outputs of the simulation tool. The tool has been tested internally by the industry partners, however, with positive feedback on the accuracy of the outputs. Additionally, the outputs of the model have been independently validated against an industry standard tool.

4 Illustrative case study

A fictional OWF installation campaign case-study has been developed through close collaboration with the industry partners, and is designed to be representative of the next phase of European OWFs. This case study was developed with the dual purpose of demonstrating the capability of the tool, and of evaluating the performance of the tool on a realistic problem. The input parameter values were provided by the industry partners based on their combined experience from previous OWF installation projects; however, these inputs are entirely generic and do not correspond to any specific OWF. The site is located in the North Sea 80 Nautical Miles (NM) off the East coast of the UK with an average water depth of 50 m. The site has 84 6 MW turbines giving a total of 504 MW generating capacity, one OSP with two export cables, and 89 inter-array cables. An OWF of this size can require in the region of 5000 input parameters to be specified.

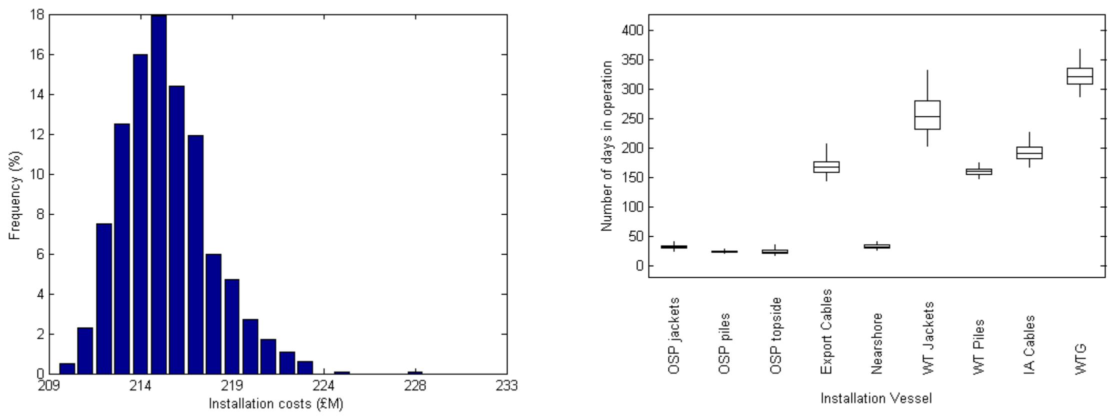
To demonstrate the potential decision support provided by the simulation tool, three different decision analysis problems are investigated. In Section 4.1 the entire installation process is modelled for a given installation scenario to obtain an understanding of the expected costs and durations of installation. In Sections 4.2 and 4.3 fleet sizing and vessel scheduling are respectively explored in the context of the WTG jacket installation vessels.

The fleet sizing investigations consider the use of either one or two installation vessels. The number of supply barges used in each case is investigated to enable the best performance in terms of cost and duration. For the vessel scheduling investigations, the start-dates for the jacket installation vessels and barges are varied with respect to the start-date of the preceding operations – in this case the pile installation process. Each set of input parameter values defines a unique installation scenario, and varying the selected parameters – the number of vessels or barges used, or the start-date of operations – gives rise to a set of installation scenarios in each analysis. As highlighted in Section 2.5 an OWF developer seeks an installation scenario which minimises capital expenditure and maximises the installation rate so that revenue from generation can be obtained. Installation scenarios are therefore compared in terms of installation costs and duration and progress of installation. Data from the FINO1 weather station [7] is used to generate the synthetic weather series.

Each installation scenario considered is investigated over N simulation runs, where N is taken to be sufficiently large to provide a robust assessment of the scenario subject to the modelled uncertainties whilst providing a tractable computation time. The total duration of working days is representative of all aspects of installation, and the robustness of the simulation output can therefore be assessed according to performance measures of the total duration found across all N simulations. A test installation scenario of the case study OWF was simulated; running 1000 simulations was found to identify both the mean and median total durations with at most 1% error at a confidence level of over 99.99%, following the approach given in [23] with the confidence interval for the median found as in [9]. Furthermore, it can be shown [9] with 99.99% confidence that 98.83% of all potential simulated total durations lie within the range of durations obtained after 1000 simulations. The simulation tool is implemented in Matlab R2014a, with inputs and outputs provided through a Microsoft Excel user interface used by our industrial partners. Performing 1000 simulation runs for the chosen installation scenario takes 3.5 hours on a 3.4 GHz dual-core processor with 8 GB RAM on a 64-bit Windows operating system, which is deemed to be tractable for the anticipated application of this method in practice. In the results presented in Sections 4.1-4.3 the number of simulations, N, is therefore set to 1000.

4.1 Analysis of an installation scenario over the entire installation process horizon

The entire installation process is modelled for a specific installation scenario to provide an understanding of the variation in costs and duration. Figure 2a shows the frequency distribution of the costs of the installation process and demonstrates the potential variance which can be expected. The median total cost of installation is £233.89M with a standard deviation of £11.80M (approximately 5%), and 95% of costs found are contained within the range (£216.28M,£262.19M), or (-7.53%, $+12.10\%$). In Figure 2b the durations for each asset installation vessel are shown as box plots, with the range covering 95% of each distribution. Both the costs and durations are positively skewed, which indicates that substantial reductions to the median values are less likely than substantial increases. The 95% ranges found in each case are relatively tight around the medians; however, there is reasonable probability for deviations in the order of tens of millions of GBP. This indicates that a developer would be justified in attempting to reduce any uncertainties in the input parameters, where possible, in order to reduce the risk of substantial deviations from the predicted median values. The duration of the WT jacket installation operations is shown to have a comparatively high level of uncertainty, which motivates further investigation of these tasks in the following sections.



(a)

(b)

Figure 2: (a) Frequency distribution for the total cost of installation, and (b) box plots of the duration of each installation vessel, for the selected scenario

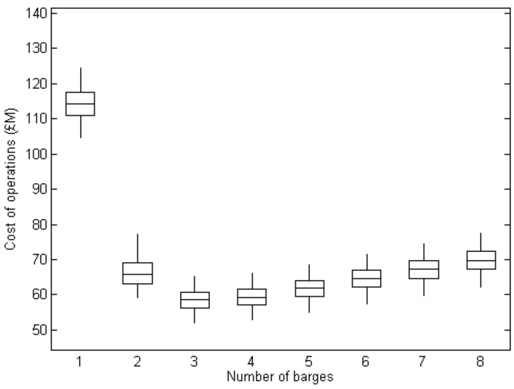
4.2 Fleet sizing for the turbine jacket installation vessels

With the WT foundations installed through a pre-piling approach, installation of a WT jacket at a given location is dependent on the pile installation process being completed beforehand. In this investigation, the jacket installation process is therefore started one year after the pile installation process to avoid any delays from the piles, so that comparisons between the different fleet sizes are equitable and performance is based purely on the number of installation vessels and barges used. The mobilisation of supply barges is managed such that the installation vessel(s) will not be delayed by waiting for supply barges to arrive on-site for the first time. The costs and duration from using one jacket installation vessel with various numbers of supply barge in support are displayed in Figure 3. The overall trend in Figure 3a indicates that the number of barges used will impact on costs, with the median costs minimised for the three barge scenario. In Figure 3b the overall trend indicates that using more supply barges will reduce the median duration, although using more than four barges is shown to provide minimal improvements to the median duration.

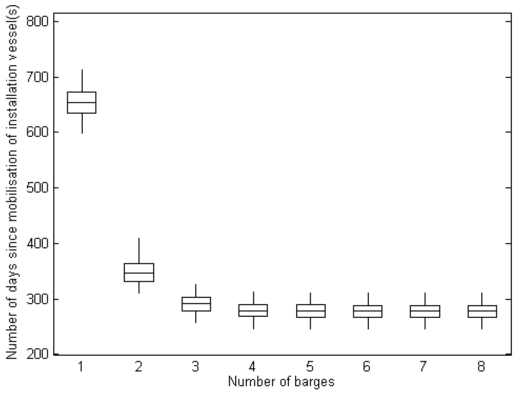
A more robust investigation of these results is performed using Kruskal-Wallis post-hoc tests [21], to identify if statistical differences exist between the medians shown in Figure 3. This is followed by applying Dunn's multiple comparisons test [12] to identify which scenarios are statistically different. This process reveals that at the 1% significance level there is sufficient evidence to suggest that the median cost obtained for the three-barge scenario (£58.55M) is statistically different to the median costs obtained for the two- and four-barge scenarios (£65.72M and £59.25M, respectively). At the 1% significance level there is found to be insufficient evidence to suggest that the median durations found with between four and eight supply barges used are statistically different; however, there is sufficient evidence to suggest that the median duration found with four supply barges (279 days) is statistically different to the median duration found with three supply barges (291 days).

Figure 4 plots the progress of the installation process for each barge scenario and demonstrates that the behaviour shown in Figure 3b is replicated throughout the entire installation – as the number of supply barges used is increased up to four, progress continues to improve, with further increases providing limited benefits. Taking both cost and duration into consideration, the use of either three or four supply barges performs well, with the respective medians shown to be statistically different at the 1% significance level for both cost and duration. The four barge scenario reduces the average installation process duration by 12 days while costs increase by £700k on average in comparison with the three barge scenario. Provided with this information an OWF developer would be able to select the best scenario based on the demands and requirements of an individual project.

The use of supply barges supporting two jacket installation vessels is investigated in a similar way. The impact on cost and duration is shown in Figure 5a and 5b, respectively, with similar trends to those shown in Figures 3a-3b. Analysing the costs reveals that there is insufficient evidence to suggest that the medians found with six, seven or eight supply barges are statistically different at the 1% significance level; however, there is sufficient evidence to suggest



(a)



(b)

Figure 3: Boxplots showing the distribution of jacket installation process (a) costs, and (b) durations, for one installation vessel supported by between 1-8 supply barges

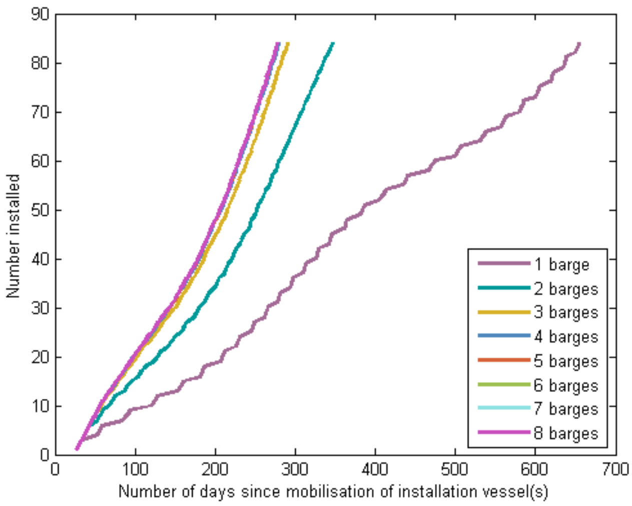
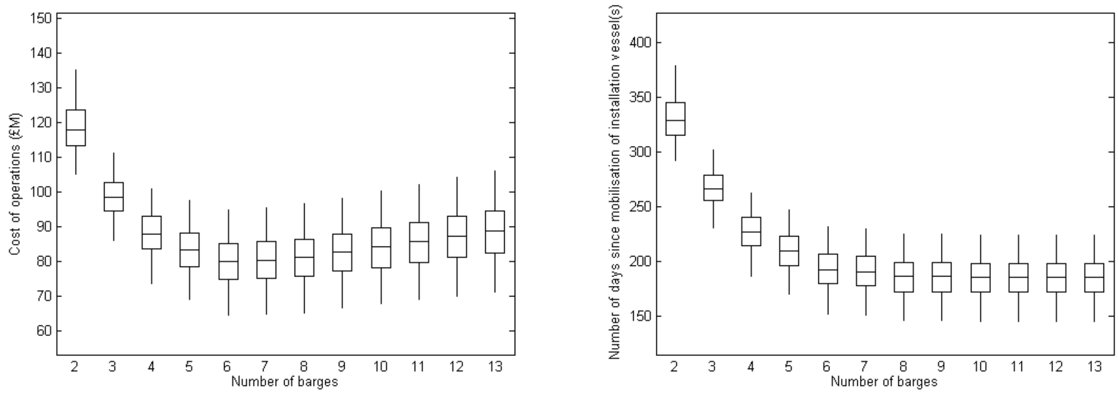


Figure 4: Average progress of the jacket installation process as the number of supply barges used to support one installation vessel is varied

that these median costs (£79.98M-£81.25M) are statistically different to those found with five barges and with nine barges (£83.36M and £82.79M, respectively) at the 1% significance level. Furthermore, at the 1% significance level there is found to be insufficient evidence to suggest that the median durations with between eight and 13 supply barges used are statistically different, whereas there is sufficient evidence to suggest that the median duration found using eight supply barges (186 days) is statistically different to the median duration when seven supply barges are used (190 days). From this analysis, the eight supply barge scenario arguably provides the best combination of both median cost and duration, with no other scenario providing statistically significant improvements.



(a) (b)

Figure 5: Boxplots showing the distribution of jacket installation process (a) costs, and (b) durations, for two installation vessels supported by between 8-13 supply barges

4.3 Vessel scheduling

The final stage in the management of the jacket installation operations is to determine an appropriate starting date for installation. In Section 4.2 jacket installation starts one year after the pile installation process to avoid any delays from the progress of the piles. In reality an OWF developer would seek the best starting date for jacket operations such that a combination of minimal delays from piling and earliest completion of jacket operations is achieved. To investigate this balance Figure 6 shows the normalised costs and completion dates to install 25% and 100% of jackets, for the jacket installation scenario with two vessels supported by eight barges, as the start date for jacket operations is varied relative to the start date of the pile installation operations. There are two factors which can explain the behaviour of the costs and durations shown in Figure 6. The first factor is that the average installation duration for a WT jacket is quicker than that for the piles at a given WT location. Starting the jacket installation too soon relative to the pile installation will therefore cause delays to the jacket installation, and will incur unnecessary costs as the jacket installation vessels and barges are frequently inactive. The second factor is that offshore operations during the winter months are exposed to harsher weather conditions whereas operations during summer months are subject to more favourable conditions. From Section 4.2 the duration of jacket installation is approximately 6-7 months, and appropriate scheduling of installation can therefore exploit the summer conditions whilst largely avoiding winter conditions.

For the installation schedule investigated here the pile operations commence on April 1st.

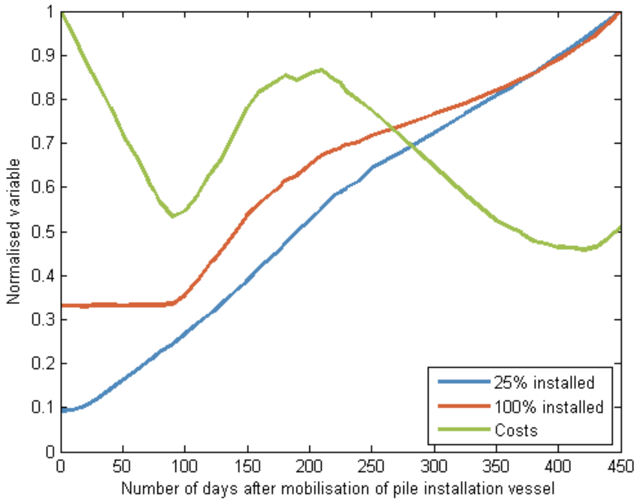


Figure 6: Average installation process costs and duration at 25% and 100% of jackets installed, as the mobilisation date of two jacket vessels and 12 barges is varied

This date represents the start of the financial year and enables installation operations to capitalise on the favourable weather conditions over the summer months, and would therefore be an appropriate choice. Starting jacket operations at the same time incurs many delays and gives high costs, but gives the earliest possible completion date. Up to approximately 90 days the jacket installation process is still delayed by the piles, finishing as soon as possible once piles are completed; however, starting later reduces delays and therefore reduces costs. Beyond 90 days the delays due to pile installation become less prominent; however, delays due to weather conditions begin to influence operations. The jacket installation is no longer restricted by the pile installation, and a later start date will therefore lead to a later completion date. A jacket start date approximately 90 days after the pile start date is at the start of July; by this point the installation period has less overlap with the spring-summer months and begins to cross into the winter months, resulting in increased weather delays. Starting jacket operations later increases the exposure to winter conditions and reduces the opportunity to exploit summer conditions. Weather delays therefore increase, causing increases to costs and increases to the rate-of-change of completion dates. Beyond approximately 210 days, which gives a jacket start date in October, exposure to winter conditions begins to decrease with increasing exposure to summer conditions. Delays due to weather start to decrease beyond this date, reducing installation costs and reducing the rate-of-change for the completion dates.

The optimal strategy should minimise delays due to the pile installation and minimise delays due to weather conditions, and Figure 6 indicates that there are two potential choices to achieve this. Starting jacket operations approximately 90 days after pile operations is sufficient to avoid delays due to the pile installation, and seems to avoid substantial delays due to weather conditions. Alternatively, both types of delays can be minimised by starting jacket operations the year after pile operations, with a start date approximately 420 days later. This would enable summer conditions to be fully exploited without incurring delays due to pile installation. The second option would give the overall least cost, whereas the first option would be slightly more expensive but would enable jacket operations to be completed substantially quicker. The information provided in Figure 6 would enable an OWF developer to compare the various starting dates and decide which is most appropriate for their particular installation project.

5 Application in practice

The case study presented in Section 4 was created in collaboration with industry partners to test the capability and illustrate the benefits of the tool. Furthermore, the tool has been used in practice by one industry partner to support logistical decision making on a current OWF installation project. SSE Renewables (a subsidiary of SSE, a leading UK energy firm) are the majority owner of the Beatrice offshore wind farm, which is currently under development and will be situated off the North-East coast of the UK. The Beatrice wind farm is expected to span approximately 131 km^2 with almost 600 MW generating capacity, and comprise 84 WTGs and two OSPs [36]. The Beatrice project is currently in the planning phase of development, with offshore installation operations expected to begin in 2017 and final completion expected in 2019. To support decision making for the logistical planning of the Beatrice installation, SSE Renewables have utilised the installation simulation tool presented here.

The tool was employed from the earliest stages of the planning and scheduling process to develop an installation schedule for which the uncertainty regarding the various stages of completion were investigated in detail, and the associated risks of over-run and bottlenecks analysed, characterised, and ultimately mitigated where possible. Rather than starting from an existing schedule and seeking to improve this, logistical installation decisions were iteratively explored and fine-tuned by providing a detailed analysis and comparison of alternative decisions. Due to commercial sensitivity it is not possible to provide full details of the work carried out to-date; however, the investigations were similar to those presented in Section 4, and decisions investigated include the selection, operation and use of alternative installation vessels, and the scheduling of different stages of the installation. The fidelity provided by the simulation tool enabled alternative installation methods to be compared, where each method consists of alternative operations, their durations and weather limits, and the particular sequence in which they are performed. The tool allows each method to be analysed in context throughout an entire installation campaign, and provides a means of comparison between alternatives which would be challenging without this tool.

Impact for SSE Renewables from using this tool has been realised in two ways. First, the tool provided the company with a means to challenge and refine the installation methods and schedules submitted by subcontractors during contract negotiations. This yielded lower expenditure and financial risks and SSE Renewables have estimated that the use of this tool has delivered a saving of approximately 14% (tens of millions of GBP) of the installation costs. Second, the tool has enabled SSE Renewables instill confidence in their regulators and investors by presenting a methodically interrogated installation plan, in conjunction with a suite of “what-if” scenarios and accompanying analysis. Gaining this confidence plays a major role in determining whether or not the Beatrice wind farm is awarded final investment to proceed with the installation, and ultimately deliver a valuable generating asset to the company.

6 Conclusions and further work

This paper presented a discrete-event simulation tool designed to provide decision making support to OWF developers. The tool was developed through collaboration with three companies involved in OWF installation and combined a realistic model of the installation process with a synthetic weather-series model. This combination enabled the comparative risks and benefits of a wide variety of logistical installation decisions to be identified. The capability of the tool was demonstrated on a fictional case study, designed to be representative of the next phase of European OWF developments, by exploring various logistical installation decisions and identifying their impact on the installation cost and duration. Furthermore, the utilisation of this tool to support logistical decision making for a real OWF installation project was discussed.

This simulation tool supports OWF developers with logistical installation decisions at the planning or bidding phase of an installation project. In parallel to this tool, the project has developed a complimentary decision support tool which can be employed by OWF developers during the course of an installation project to identify appropriate reactions to disruptions to the installation schedule [4]. This work develops an optimisation model of the OWF installation which combines a rolling horizon model with a robust optimisation model. By restricting the scope of the decision space and installation model to the existing state of the installation and realistic decisions which would be pursued, this optimisation tool is capable of providing analytic solutions to the complex OWF installation logistics problem which builds upon the work presented here.

During the course of this project several areas of decision making have been identified as critical to the OWF installation process, in addition to the logistical and operational decisions discussed here and future work will extend the scope of this decision-support tool to incorporate these factors explicitly. In practice various sources will be considered for each asset, with varying manufacturing and transportation costs, and the storage requirements for larger assets can be problematic. Additionally, there are a variety of considerations related to the layout of the OWF which can impact on the installation process, including the geo-technical characteristics throughout the site and the design of the cable network. It would be desirable to include these considerations explicitly within a decision-making tool so that the supply chain, inventory, and the layout can be optimally managed in conjunction with the installation schedule.

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References

[1] Agency, I.R.E.: The power to change: Solar and wind cost reduction potential to 2025 (2016). `http://www.irena.org/DocumentDownloads/Publications/IRENA_Power_to_Change_2016.pdf` (Last accessed 22nd August 2016)

[2] Ait-Alla, A., Quandt, M., Lutjen, M.: Aggregate installation planning of offshore wind farms. In: Proceedings of the 7th international conference on communications and information technology, pp. 130–135 (2013)

[3] Arhami, M., Kamali, N., Rajabi, M.M.: Predicting hourly air pollutant levels using artificial neural networks coupled with uncertainty analysis by monte carlo simulations. Environmental Science and Pollution Research **20**(7), 4777–4789 (2013)

[4] Authors names removed for double blind review: A rolling horizon optimisation model for offshore wind farm installation logistics (2016). In preparation

[5] Bauer, P., Thorpe, A., Brunet, G.: The quiet revolution of numerical weather prediction. Nature **525**(7567), 47–55 (2015)

[6] Brailsford, S., Churilov, L., Dangerfield, B.: Discrete-Event Simulation and System Dynamics for Management Decision Making. John Wiley & Sons, Chichester, UK (2014)

[7] Bundesministerium fuer Umwelt, Projekttraeger Juelich: FINO 1 Meteorological Dataset 2004 - 2012 (2012). `http://fino.bsh.de` (Last accessed 1st December 2012)

[8] Christiansen, M., Fagerholt, K., Nygreen, B., Ronen, D.: Ship routing and scheduling in the new millennium. European Journal of Operational Research **228**(3), 467–483 (2013)

[9] Conover, W.J.: Practical nonparametric statistics. John Wiley & Sons, New York (1980)

[10] Darabi, Z., Ferdowsi, M.: An event-based simulation framework to examine the response of power grid to the charging demand of plug-in hybrid electric vehicles. IEEE Transactions on Industrial Informatics **10**(1), 313–322 (2014)

[11] Dinwoodie, I.A., McMillan, D.: Operational strategies for offshore wind turbines to mitigate failure rate uncertainty on operational costs and revenue. Renewable Power Generation, IET **8**(4), 359–366 (2014)

[12] Dunn, O.J.: Multiple comparisons using rank sums. Technometrics **6**(3), 241–252 (1964)

[13] Dunn, W.L., Shultis, J.K.: Exploring Monte Carlo Methods. Elsevier, Oxford, UK (2011)

[14] Endrerud, O.E.V., Liyanage, J.P.: Decision support for operations and maintenance of offshore wind parks. In: Engineering Asset Management-Systems, Professional Practices and Certification, pp. 1125–1139. Springer, London (2015)

[15] European Wind Energy Association: Wind in our sails (2011). http://www.ewea.org/fileadmin/ewea_documents/documents/publications/reports/23420_Offshore_report_web.pdf (Last accessed 22nd August 2016)

[16] European Wind Energy Association: Deep water (2013). http://www.ewea.org/fileadmin/files/library/publications/reports/Deep_Water.pdf (Last accessed 22nd August 2016)

[17] Gharehgozli, A.H., Laporte, G., Yu, Y., de Koster, R.: Scheduling twin yard cranes in a container block. Transportation Science **49**(31), 686–705 (2014)

[18] Golias, M., Portal, I., Konur, D., Kaisar, E., Kolomvos, G.: Robust berth scheduling at marine container terminals via hierarchical optimization. Computers & Operations Research **41**, 412–422 (2014)

[19] Irawan, C.A., Jones, D., Ouelhadj, D.: Bi-objective optimisation model for installation scheduling in offshore wind farms. Computers & Operations Research (2015). http://dx.doi.org/10.1016/j.cor.2015.09.010

[20] Jung, J., Onen, A., Russell, K., Broadwater, R.P., Steffel, S., Dinkel, A.: Configurable, hierarchical, model-based, scheduling control with photovoltaic generators in power distribution circuits. Renewable Energy **76**, 318–329 (2015)

[21] Kruskal, W.H., Wallis, W.A.: Use of ranks in one-criterion variance analysis. Journal of the American statistical Association **47**(260), 583–621 (1952)

[22] Lange, K., Rinne, A., Haasis, H.D.: Planning maritime logistics concepts for offshore wind farms: a newly developed decision support system. In: Computational Logistics, pp. 142–158. Springer, London (2012)

[23] Law, A.M., Kelton, W.D., Kelton, W.D.: Simulation modeling and analysis, vol. 2. McGraw-Hill, New York (1991)

[24] Lutjen, M., Karimi, H.R.: Approach of a port inventory control system for the offshore installation of wind turbines. In: The Twenty-second International Offshore and Polar Engineering Conference, pp. 502–508 (2012)

[25] Mojo Maritime Ltd: Mermaid (2016). http://mojomermaid.com/ (Last accessed 22nd August 2016)

[26] Morandeau, M., Walker, R.T., Argall, R., Nicholls-Lee, R.F.: Optimisation of marine energy installation operations. International Journal of Marine Energy **3**, 14–26 (2013)

[27] Muhabie, Y.T., Caprace, J.D., Petcu, C., Rigo, P.: Improving the installation of offshore wind farms by the use of discrete event simulation. In: Proceedings of the 5th World Maritime Technology Conference (2015)

[28] Niziolek, L., Chiam, T.C., Yih, Y.: A simulation-based study of distribution strategies for pharmaceutical supply chains. IIE Transactions on Healthcare Systems Engineering **2**(3), 181–189 (2012)

[29] Offshore Wind Cost Reduction Task Force : Offshore wind cost reduction task force report (2012). `https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/66776/5584-offshore-wind-cost-reduction-task-force-report.pdf` (Last accessed 22nd August 2016)

[30] Quiring, S.M., Schumacher, A.B., Guikema, S.D.: Incorporating hurricane forecast uncertainty into a decision-support application for power outage modeling. Bulletin of the American Meteorological Society **95**(1), 47–58 (2014)

[31] Roberts, A., Weston, J., Valpy, B.: Offshore wind: a 2013 supply chain health check (2013). `https://www.thecrownestate.co.uk/media/5483/ei-km-in-sc-supply-112013-offshore-wind-a-2013-supply-chain-health-check.pdf` (Last accessed 22nd August 2016)

[32] Robinson, S., Worthington, C., Burgess, N., Radnor, Z.J.: Facilitated modelling with discrete-event simulation: Reality or myth? European Journal of Operational Research **234**(1), 231–240 (2014)

[33] Scholz-Reiter, B., Lutjen, M., Heger, J., Schweizer, A.: Planning and control of logistics for offshore wind farms. In: Proceedings of the 12th WSEAS international conference on Mathematical and computational methods in science and engineering, pp. 242–247 (2010)

[34] Shafiee, M.: Maintenance logistics organization for offshore wind energy: current progress and future perspectives. Renewable Energy **77**, 182–193 (2015)

[35] Shyshou, A., Gribkovskaia, I., Barceló, J.: A simulation study of the fleet sizing problem arising in offshore anchor handling operations. European Journal of Operational Research **203**(1), 230–240 (2010)

[36] SSE: BOWL Presentation (Beatrice Project Update) (2015). `http://sse.com/whatwedo/ourprojectsandassets/renewables/Beatrice/` (Last accessed 22nd August 2016)

[37] Stempinski, F., Wenzel, S., Lüking, J., Martens, L., Hortamani, M.: Modelling installation and construction of offshore wind farms. In: ASME 2014 33rd International Conference on Ocean, Offshore and Arctic Engineering, p. Article ID V09BT09A001 (2014)

[38] Tejada, J.J., Ivy, J.S., Wilson, J.R., Ballan, M.J., Diehl, K.M., Yankaskas, B.C.: Combined DES/SD model of breast cancer screening for older women, I: Natural-history simulation. IIE Transactions **47**(6), 600–619 (2015)

[39] Wang, Z., Li, P., Li, L., Huang, C., Liu, M.: Modeling and forecasting average temperature for weather derivative pricing. Advances in Meteorology **2015**, Article ID 837,293 (2015)

[40] Williams, T.: Practical use of distributions in network analysis. Journal of the Operational Research Society **43**(2), 265–270 (1992)

[41] Yuan, T., Zhu, X.: Reliability study of ultra-thin dielectric films with variable thickness levels. IIE Transactions **44**(9), 744–753 (2012)