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Assessment approaches to logistics for offshore wind energy installation

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ABSTRACT

Offshore wind farm installation planning is highly complex, due to the high dependency on weather and the oversized components that impose specific constraints in areas such as transportation and lifting. Currently, there is very little transparency vis-à-vis the logistics challenges in the industry. We extend the literature by creating an overall view of the coherency between logistical methods and project performance. We develop knowledge about how to use the various approaches by analyzing different logistical solutions. A holistic view of the coherency between the approaches in terms of logistics and project performance, taking into consideration the external influence of weather, is provided through analysis of actual projects in the North Sea region. Case study findings reveal the major factors to be pre-assembly, vessel load, and the distance to shore. We suggest a pre-assembly strategy comprised of a minimum number of components for installation onsite and a maximum number of turbines to be loaded on a vessel. These findings are especially important for the new wind farms being positioned further offshore. We show by means of a case study, with specific characteristics and weather conditions, that the appropriate strategies can be arrived at by using a simulation-based decision-support tool we developed.

Motivation

With today's technological society and with significant developments such as internal combustion engines in transport, our energy consumption has increased more than a hundredfold within the past few decades [1]. Continuing rapid growth is foreseen, and the challenge today is to move away from our heavy dependence on fossil fuels and towards wider use of renewable energy resources. Concerns about sustainability, the environment, and climate change are major reasons driving this shift. The use of fossil and nuclear resources increases the side effects of supplying energy, such as the emission of greenhouse gases and the risk of nuclear accidents. Moreover, the limited supply of fossil-fuel resources and restricted access makes exploitation more and more difficult. In the long run, fossil fuels like oil will become scarce, and more and more expensive. The European Union's commitment to reducing CO_2 emissions, as well as rising oil prices, makes renewable energy increasingly important as an alternative energy source [2].

As a cost-effective and clean way of generating energy with the help of nature, wind energy is seen as one of the most viable options in reducing the ecological footprint [3]. The wind power industry is expected to continue growing in the coming decades. However, the industry is facing another challenge. The possibilities for increased numbers of onshore wind farms are limited as the generation potential in the countryside becomes more restricted [4]. Consequently, the shift from onshore to offshore is inevitable [5].

Compared to onshore, offshore has its advantages, such as the high potential of wind energy over the sea, less visual pollution, and the large availability of space that allows for larger-scale projects [6]. Those countries with coastal areas, especially, are highly interested in developing offshore wind projects. However, the economic aspects of offshore wind projects are currently less favorable compared to onshore. As of 2011, offshore wind projects were at least three times more expensive than onshore wind projects of the same nominal power [7].

Past research on the offshore wind industry has been mainly focused on the technical challenges in the design, manufacturing, installation, and operation of the facilities. A categorization of past research, based on the different phases of wind turbine operations, reveals that studies about the maintenance and operation of offshore wind turbines are denser compared to the installation phase. Within the first category, a plethora of researchers [8–11] have worked on scheduling models for the maintenance of offshore wind turbines. A recent paper in *renewable energy* [12] comprehensively reviews the past research on maintenance logistics. For the daily operation of wind turbines constructed offshore, more scheduling models have been studied in order to minimize cost

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[13–15]. For the second category, that is, logistics operations in the installation phase of a wind farm, the activities involve the port and are related to the pre-assembly of components, transportation to the site, and installation at sea. Relatively little research has focused on the logistics involved in this installation phase of the offshore wind industry. However, in this regard, Scholz-Reiter and colleagues [16] have proposed a mixed-integer linear programming model for the installation of offshore wind turbines. Ait-Alla and colleagues [17] have provided an aggregate planning method for minimizing the installation cost, with capacity and weather conditions being considered as deterministic parameters. Uraz and Emre [18] have identified the factors involved in the offshore turbine installation phase, which is highly necessary in order to understand the ways that installation performance can be improved vis-à-vis various special conditions. This study created an approach for time-wise modeling of the transportation and installation process of offshore wind turbines in order to figure out the effect of different parameters on the overall duration. However, it should be noted that the consideration given to uncertainty and disruptions during the installation remains a vital part of real-life operations and still needs to be addressed [19–21]. Accordingly, Lütjen and colleagues [22] have presented a simulation approach focusing on a different aspect of a wind farm project, which involves inventory control of offshore wind turbines. There is hardly any transparency involved in the logistics of the wind power industry [16]. In particular, the impact of weather conditions on the supply chain complicates any decision regarding a holistic logistical concept, and this is crucial for an economic setup. Based on these factors and the current research gap, this study fits within the definition of the second category, that is, the installation phase. It adds to the existing literature by considering the disturbances due to weather conditions during the installation phase and provides a decision-support tool that can be used for analyzing the various effects of employing different logistics approaches.

The significance of and need for further studies on the installation phase of wind farms has been underlined by industry facts. Installation at sea is complex, and the equipment necessary is highly expensive. An important challenge for the management of offshore wind projects involves its highly complex planning. The installation of the first wind-power projects was considerably delayed. The influence of weather conditions in terms of restricting time windows for the installation of wind turbines at sea was dramatically underestimated. For example, although the North Sea region has numerous features that make incorporation of renewable energy sources attractive, such as large wind resources and huge hydro reservoirs in the North, installation in the North Sea region is only possible for about 120 days a year [23,24]. The large components of the turbines' structure are highly vulnerable to wind. Hence, installation processes like lifting are restricted to a certain wind speed range. These delays impact project timelines considerably, resulting in huge unforeseen costs [25]. Managing the logistics so that turbines and vessels are in the right place at the right time is a major challenge. Resulting logistical decisions have a significant impact on profitability. The logistics costs of the tower installation phase are estimated at 15–20% of the total cost [26]. The wind power industry is currently facing a new challenge in terms of the planned construction of installations totaling six GW (gigawatt) in capacity to meet the EU target of 20% renewable energy production in 2020 [27]. To be economically feasible, more research needs to be done to develop improved and more efficient handling of logistics activities.

As stated previously, the logistics operations within the installation phase of a wind farm involve the activities at the port related to the pre-assembly of components, transportation to the site, and offshore installation at sea. At sea, the installation of a complete wind turbine structure is divided into two stages: the installation of the foundation and the turbines. The construction of the foundation and its transition pieces are completed first. After this, once the transition piece creates a level connection surface for the turbine, the installation of the turbines can be completed. This study focuses on the turbine installation phase. We will be considering the logistics activities involved in the installation process of turbines, which impacts on the overall project performance. In practice, different logistical methods are used in the offshore wind turbine installation phase. Within these methods, pre-assembly plays an important role in turbine installation. Different levels of pre-assembly of parts onshore instead of assembly onsite can be employed. The purpose of pre-assembly is to partly overcome challenges from the dependency on weather conditions, which is the main cause of project delays [1]. Through the effective and correct use of the pre-assembly concept, installation time can be reduced [28]. However, it is still not yet clear which characteristics of these logistical methods influence project performance and to what extent they influence it. Much may also depend on project specifics such as the distance to shore and local weather conditions. In this study, we will focus on the logistics methods employed during the installation phase of the turbines, which is seen as the key to efficiency in the industry.

This paper contributes to the literature by creating an overview of the relationship between logistical methods and project performance in terms of total installation time and installation costs. As a result, the transparency of the logistics involved in the installation phase in offshore wind can be increased. This matter is of paramount importance in light of the need for greater support in making efficient choices among logistics methods for future projects. This need is made more crucial due to the projects planned in the North Sea region within the next decade. To be able to support decision-makers, an analysis of the influences of the various logistical approaches on project performance for offshore wind projects needs to be undertaken. To accomplish this, first, the specific characteristics of the logistical methods and the influence of weather need to be investigated. Second, it is necessary to know how the different logistics approaches influence project performance. This will provide a more accurate understanding of the use of different logistical approaches and will serve as the basis for the development of a decision-support tool aimed at an efficient supply-chain network design. Finally, a decision-support tool to support assessment of logistics approaches for various project specifications will be developed and will proceed to be implemented in a wind farm installation project in the North Sea.

The remaining parts of this paper are organized as follows. In Section II, the characteristics of the logistics methods used in the offshore wind tower installation will be described. Identification of the essential requirements for offshore network design has primarily been achieved through discussions with experts in the field along with project data. For evaluation and assessment of these consultations with experts, data obtained from the offshore wind project "BARD 1" in the North Sea will be utilized. Section III will then present the structure of the simulation-based decision-support tool. In Section IV, the "BARD 1" project will be described, and the use of the decision-support tool will be illustrated. Following that, the results of additional experiments will be described. Finally, Section V will enumerate the managerial insights and conclude the study.

Offshore wind turbine installation characteristics

This section will provide an in-depth analysis of the problem in order to reveal the characteristics of the various logistics methods. Network characteristics and configurations will be explained, along with the important aspects of the installation phase.

The offshore wind industry is characterized by medium-sized manufacturers and suppliers who are driven by the growth of the market, campaign-based planning, short-term scheduling due to influences from weather conditions, and constraints due to scarce and costly resources (e.g., limited number of purpose-built installation vessels) [26]. Most manufacturers and suppliers are new players in the market, and the network configurations are temporary, lasting only until the projects are finished. Since the installation network is designed by the project developers, those companies involved in the installation are forced to adapt to the project's logistical decisions. For instance, installation vessels are hired for limited periods of time, since they are extremely expensive. Therefore, they need to be used as efficiently as possible. However, uncertainty and disturbances from weather make planning possible in the short term only. Consequently, it is crucial to pick the right logistics methods with efficiency in mind. Conversely, discussions with experts in the field and project data have revealed that current practice lacks efficient consideration of the influences of weather. As a result, modern network design tools are required, in which the experience from long-term projects can be embedded, in order to support decision-making on a project level.

The installation phase is an inevitable bottleneck in the supply chain mainly because of the dependency on weather, which causes interruptions in the maritime portion of the supply chain. On the one hand, the upstream stages of supply-chain manufacturers produce their parts on schedule, while, on the other hand, the installation phase may be interrupted by weather. This inevitably leads to the formation of stock backups within the supply chain.

Another characteristic of the offshore wind industry is that it has to deal with components that are large, heavy, and fragile. Storing these components requires a large area specially prepared for these enormous structures. To support this, ample storage at the port is used as part of the logistical inventory. One reason for this is that space is most easily available at a port, where the facilities required are present, such as the lifting equipment. Another reason is the rental rates for installation vessels, which are very high. Project leaders will aim to maximize the utilization of the vessels when leased. Storing the components at the port minimizes the risk of delay, as the components are available when needed.

This factor, along with the ever-present dependency on weather, indicates that the staging port must be available 24 h a day, 7 days a week. Both the availability of wind turbine components and of construction vessels are critical elements of the offshore wind turbine installation network.

The processes within the installation part of the supply chain are illustrated in Fig. 1. Offshore wind turbines are constructed using several components. These components can be pre-assembled in several ways. To prevent delay, multiple turbines are prepared before the loading process starts. When a vessel is in port, it will be loaded with the turbine components as soon as the weather is good. The high lifting required for large components is restricted by wind speed. The vessel will be loaded with complete turbines as efficiently as possible, meaning that it will only leave the port with the maximum number of turbines loaded.

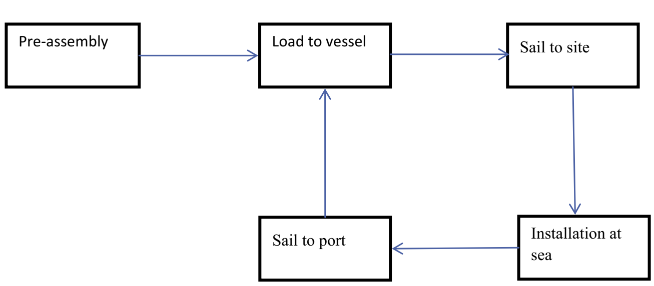

Fig. 1. Processes at offshore wind installation.

Due to safety consideration, activity by the vessels is constrained by wave height and wind speed. The components catch a lot of wind, and so shipment of these enormous components is generally constrained by wind speed limits. While wave height and wind speed are correlated, practice shows that the wind speed limit is reached earlier than that of wave height. When the vessel is fully loaded and the weather is good, it can journey to the site where the turbines are to be installed.

Before lifting at sea, the vessel needs to be jacked up. Sealifting is also restricted by weather, and forecasts need to be evaluated for each action. This also applies between lifting the components. The tower sections are installed first, followed by the nacelle and the hub. The next step is to attach the blades to the hub. However, as noted, the turbine components can also be transported pre-assembled to site. After all the components are in place, the ship returns to the port to be loaded again.

Weather plays a decisive role in the selection of the sites and in the operational planning. The fundamental purpose of installing wind turbines is to utilize wind energy as much as possible [29,30]. Accordingly, the offshore sites selected for offshore wind projects are likely to have high wind speeds, which also result in significant wave heights. This affects the installation process significantly. The wind and sea conditions always limit and narrow the time window for safe installation. The time window is crucial and must be calculated accurately to prevent risky and hazardous situations that may occur on the trip or at the site. In case the weather turns bad when the turbine is shipped to the site operations are stopped immediately. Formerly, due to the uncertainty of the weather and less accurate weather forecasts, use of two different procedures in the field was common. In the summer, a single task (for example, one component lift) may start when it can be accomplished within a good weather forecast. In winter, a cycle from loading, shipment, installation, and returning to port could only start if the weather forecast is clear of stormy weather for the complete cycle. This means that there should be no bad weather within the forecast of the complete cycle. With modern satellites the use of winter procedures are now less often used.

An important aspect of offshore wind farms is the distance from the shore to the site. Increased distance, and hence increased travel times, calls for vessels with larger cargo capacities, which in turn has specific upsides and downsides. Larger vessels can offer larger deck space and high lifting capacities, making them on the other hand less agile and costly to operate [31].

The power capacity of offshore wind turbines is increasing, as turbine technology continues to develop. Today the common offshore wind turbine is 5 MW, and even larger machines are expected in the near future. This increase in the size of the machines adds to the challenges for offshore installations. Offshore turbine installations require lifting heavy components and placing them at predetermined heights. The increased volume of the turbine components occupies more space on the installation vessel, which then decreases the number of turbines that can be placed on the deck at one time. For logistical strategies at sea, there are two possibilities known in the literature: the all-in-one and the feeder system. In the all-in-one strategy, the installation vessel also transports the components. The vessel is loaded at the base port and transports the parts to the installation site. There, the plant components are installed section by section by the same installation vessel. No unloading processes are needed. Once the installation process is complete, the vessel returns to port to pick up the next components. In the feeder system, the installation unit stays at the wind farm. It is supplied by smaller "feeder" vessels or barges, which bring the necessary components from one or more ports to the site. Since there are no travel times for the installation unit in this scenario, productivity can be higher. However, due to the growth in size of the components, the coordination for lifting has become more complicated. Because of safety, this is currently only applicable for foundations. The turbine components have become too large and are too fragile to lift from another vessel at sea.

As mentioned before, offshore wind farm sites are selected especially for their high wind potentials, which limits crane operations in terms of an available time window for lifting the components safely. Since choosing a less windy site is not an option for solving this problem, different installation methods have been developed to reduce the duration of offshore works in order to fit into narrow time windows. These methods are based on carrying the components already assembled (pre-assembled) at the port. A wind turbine (without the foundation and transition piece) consists of 6 main parts: tower, nacelle, hub, and three blades. Towers are of the heaviest and largest pieces of the wind turbine. Due to this they are usually transported in 2 pieces. Hence, the number of components actually becomes seven, which in return increases the number of onshore assembly alternatives. All those approaches have either positive or negative effects on installation performance. Increasing the number of pre-assembled pieces on the deck decreases the offshore installation time, but in fact the increased volume of the assembled structures also needs to be taken into account, since it can lead to less efficient use of the available deck space of the vessel. Choosing the right logistical approach according to the specific conditions of the project site is indispensable for project efficiency.

In this study, the installation phase of a project will be evaluated on the basis of different logistical methods. Based on expert discussions and important points as indicated by project developers, the project performance of the installation is measured by the total time required and the differences in costs between logistical concepts for handling the project. Expert interviews and operational data from the "BARD 1" project have been utilized for in-depth analysis of the problem. For validation and the explanation of the decision-support tool, the "BARD 1" project will be evaluated. It should be noted that the decision-support tool was developed such that it could be used for other projects by changing the project-specific input. In the following sections, the features of the installation logistics will be discussed.

Installation phase

This section provides a comprehensive analysis of the installation phase through the use of an in-depth analysis of a case project within the North Sea region.

Projects in general are characterized by a certain number of turbines, which can vary between 30 and 150. The water depth at the installation site depends on the area. The new 5 MW turbines were placed further out from shore, where average sea depth is about 40 m.

Turbine characteristics

Turbines are assembled from 6 or 7 parts, depending on the tower structure. With the latest developments, most turbines are 5 MW, and all approximately the same size. Specific turbine type selection is a preliminary stage [33]. Due to its size, the tower is made up of two main parts. Within the analyzed case "BARD 5.0," a 5 MW turbine, featuring a 122-meter rotor diameter, 14 m-long box-type nacelle, 8.5 m wide and 8 m high, was used. As is common with most offshore wind turbines, it consists of several main components: the tower, nacelle, hub, and three blades (Fig. 2).

Installation vessel characteristics

In this study, we will consider vessels that are capable of lifting. These are dedicated vessels specially made for the offshore wind industry. Such vessels are increasingly favored, due to the growth in turbine sizes. Available vessels in the sector differ in terms of their cargo capacity. Before lifting components at sea, the vessel needs to jack up 5 m above sea level. The speed of the legs is approximately 15 m an hour. The legs penetrate the seabed for about 5 m. Research shows that the maximum load of turbines on a vessel is constrained mainly by size and not by the weight of the components [18]. The reason for that is that turbines are built to be as light as possible.

The most common financing method for a vessel is leasing for a certain amount of time. A common cost notation for a vessel is its day rate. Vessel day rates are market-driven and dynamic. Competition levels and services are primary determinants of cost, and seasonal variations often exist

Process characteristics

Expert interviews revealed that weather conditions are a negligible factor in the time taken for pre-assembly at the port. Pre-assembly on shore is avoided only in case of severe stormy weather. There is a maximum of only a few hours a year when the pre-assembly stage is blocked due to weather. In such cases, all processes are interrupted, notwithstanding the assembly method. Pre-assembly is done parallel to installations at sea, that is, all the components can be prepared while the vessel is still at sea. Real data and expert knowledge shows us that pre-assembly is always finished before the vessel arrives to be loaded, so as to not cause any delay in the process.

Costs within the pre-assembly stage are mainly dependent on the time spent on pre-assembly. The costs within the pre-assembly stage mainly arise from labor hours and facilities required. The required facilities may be different from one pre-assembly method to another. For example, a nacelle is a heavier part. When it is pre-assembled a larger crane is needed.

Weather influences

Low wind speed is required for the installation of offshore wind turbines. Each process has its own specific limits. For instance, Table 1 shows the limits that were used in the case of the "BARD 1" project. After consulting with experts, it can be concluded that, because the restrictions depend on the processes, it is plausible to assume that these limits are approximately the same for all projects. If the weather forecast exceeds the process limits, the process may not start for safety reasons. In our simulation-based decision-support tool, we relied on statistical weather data for the North Sea region between 2011 and 2013. When the weather forecast remains below the process limit, the process may start. This available time is called the weather window. For the process time, we were advised to look at the worst-case process time. Accordingly, it is important that the weather forecast indicates the state of the weather and how long this will last. Limited-area models are widely applied in order to provide weather forecasts for up to 3 days, with their forecast accuracy ranging between 80% and 90% [27].

The system also needs to take potential errors into account. When an error occurs there are two options. First, if the forecasted weather window turns out to be shorter in reality, then the process must be stopped immediately for safety reasons. When this occurs the process will be postponed until the next weather window. Second, if the weather forecast is bad but the limits are not reached, no action has to be taken.

Next, the influence of the weather will be explained in more detail with data from the North Sea area. It should be noted that the decision-support tool is capable of operating with other weather data input.

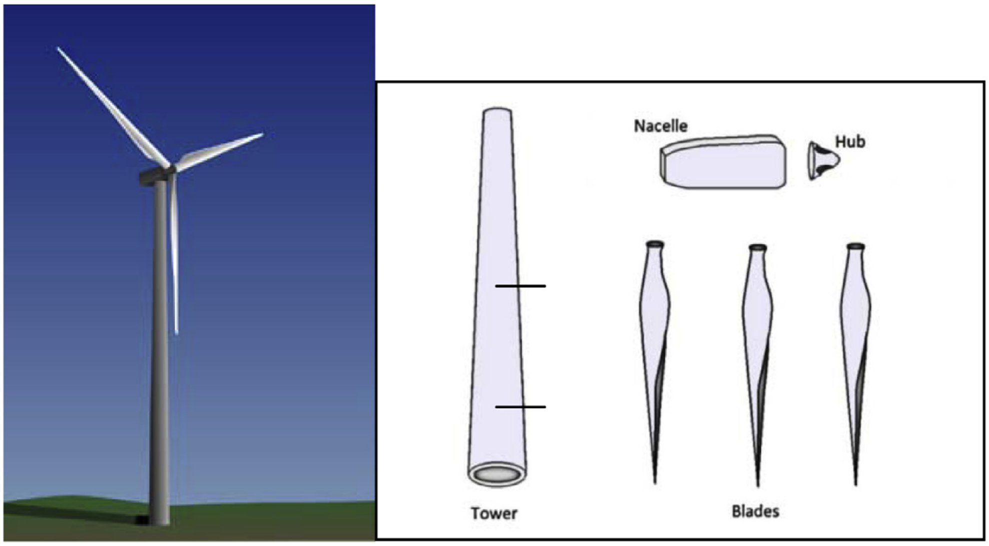

Fig. 2. Turbine and its components.

Table 1
Weather levels including wave-height and wind-speed constraints.

Lifting limit (wind speed)	10 m/s
Shipment limit (wind speed)	16 m/s

Table 2
Weather condition ranges depending on wind speed.

Level	Wind speed ranges
Lifting	<10 m/s (level 1)
Shipment (no lifting)	>10 m/s, <16 m/s (level 2)
Bad weather (no action)	>16 m/s (level 3)

Fig. 3 shows the wind speed measurements for the North Sea region. The wind speed data uses all data on time series of 1 h over a period of 2 years.

To build the forecast model, the weather conditions are divided into three levels as shown in Table 2. The three levels of the weather conditions represent the process restrictions due to the wind-speed levels. Shipment is possible during the first two levels. Therefore, it is important to know the sequence of the weather condition levels. For example, when the weather conditions are in level 1 for a period of 3 h and is followed by level 2 for a period of 3 h, a shipment of 5 h can be made. However, if, in the meantime, the weather becomes level 3, the shipment process should not start. To be able to incorporate this, we analyzed the sequence probability of the weather condition. In Fig. 4, the probability of the sequence chain is shown.

Next, we analyzed the time series to extract the distributions of the period lengths. Fig. 5 provides an example of how the data is processed. The period of time for lifting is the total time the wind speed is below the limits. With the use of this method, a frequency table for the length of periods was developed.

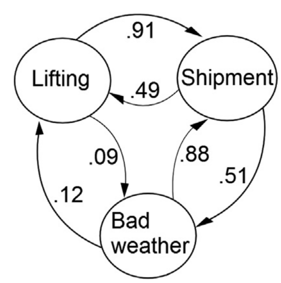

Fig. 4. Weather sequence probability chain.

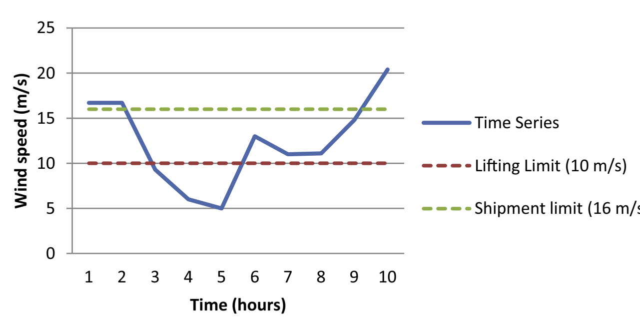

Fig. 5. Example weather data analysis.

Pre-assembly strategies

In practice, different assembly strategies are implemented vis-à-vis projects. Some projects use separate component installations, where all components are assembled at sea. There are also projects that use different onshore pre-assembly methods.

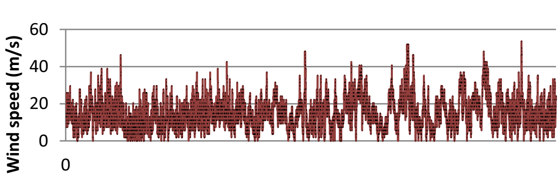

Fig. 3. Wind speed two-year time series.

Research on installation methods reveals that three main installation methods are applied in the offshore turbine industry, taking into consideration current developments in turbine technology. These are as follows:

(a) *Bunny ear*: Nacelle, hub, and two of the blades are assembled at the port, and a shape like a rabbit's head is formed, hence this method is called "bunny ear" in the offshore industry. The tower is carried in two pieces, and the third blade is also placed separately on the same boat (Fig. 6). Therefore, one turbine is transported in four pieces to the site and requires four offshore lifts at the construction site.
(b) *Full rotor star*: Hub and three blades are assembled at the port, shaping the complete rotor, also called a "full rotor star" (Fig. 7). Tower sections and nacelle are placed separately on the same boat. As a result, one turbine is transported to the site in four pieces and requires four offshore lifts at the construction site.
(c) *Separate parts*: The hub and the nacelle are assembled at the port. The tower is carried in two pieces and the blades are placed in the "blade stacker" separately (Fig. 8). As a result, one turbine is transported in six pieces to the site and requires six offshore lifts at the construction site.

Pre-assembly costs are mostly driven by labor. Other costs, such as the requirement for special lifting equipment, are also involved. Pre-assembly costs differ among different pre-assembly strategies. Differences arise, for example, because more heavy lifting equipment is needed when the nacelle is pre-assembled.

The maximum number of turbines that can fit on a vessel depends on the space available on a vessel and the space required for each turbine. The space needed for each turbine depends on the pre-assembly method used.

Performance measurement

In an offshore installation project, a distinction between internal and external performance measurements can be made. The internal performance measurements are important for the companies responsible for specific processes such as the total pre-assembly time for the pre-assembly company. However, our interest here is on the logistical decisions that are made, based on overall project performance. These comprise the external performance measurements. The most important performance measurements for project developers are total installation time and installation cost. It should be noted that the total installation time is the time it takes to finish the installation of all turbines.

Section II provides an in-depth analysis of the characteristics of the installation phase that influence supply-chain performance. To analyze how these characteristics of the logistical methods in the offshore wind tower installation influence performance, a simulation-based decision-support tool was developed. This system will be introduced in the following section.

Decision-support tool

The software was developed to run in a PC environment under Microsoft Windows. The simulation-model-driven decision-support system employs an architecture to generate solutions for user-mediated problem cases. Discrete-event simulation is used for the development of the decision-support tool. Simulation is useful when modeling projects with sequential and repetitive operations, especially when the operations are dependent on external factors [27,32]. Simulation can help with the variability, interconnectedness, and complexity of the problem. Furthermore, a more intuitive and animated display of the system can be created, increasing the system's transparency.

In the following section, the simulation-based framework for all the supply-chain processes of the offshore wind turbine installation, as described in the previous chapters, will be introduced.

Weather module

The decision-support tool employs a weather forecast module that runs parallel with the supply-chain model. The weather data is processed as discussed in Section II. Fig. 9 presents a schematic overview of the working structure of the weather module. At the start of a project, the weather is set to a certain level depending on its probability function. Next, it enters the cycle where the period length will be determined, depending on the weather conditions according to the period-length distribution. The next weather state will be determined according to the sequence probability function. These will be logged in a data file that can be recalled by the forecast process when needed to update the status shown in Fig. 9. After each cycle the model checks whether the supply chain model is finished and, if so, the simulation run can be completed.

As mentioned in Section II, the possibility of forecast error also needs to be considered. Accordingly, within the model, the error module works so as to interrupt the processes based on past error data probabilities.

Installation module

Fig. 10 shows a schematic overview of the logistics module within the decision-support tool. This overview can be summarized as follows: The model starts with the initiation of a project. All turbine component entities are created in the ample storage area at the port. From there the components are assigned to the pre-assembly stage, one by one. Pre-assembly starts whenever there is space. The turbines are delayed during the given processing time depending on the input data. Following that, the turbine will be assigned to the buffer of the pre-assembly, and the buffer will signal a turbine is placed at a counter. The turbines are converted to the components, depending on the pre-assembly strategy described in Section II.

Before loading can start, the module checks if the vessel is available and whether the weather forecast allows lifting to proceed. If not, the loading process has to wait until these conditions are met. The time needed due to weather conditions depends on the processing times. If the process can proceed, the components from the pre-assembly buffer can be assigned one by one to the loading

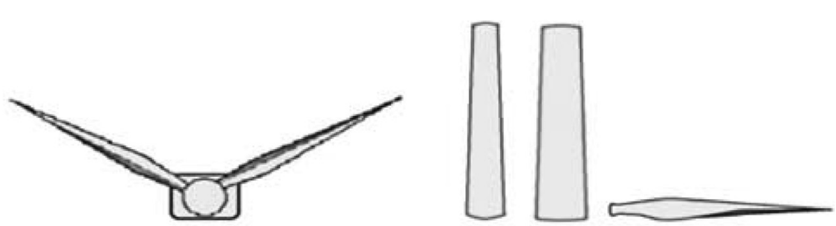

Fig. 6. "Bunny ear" composition.

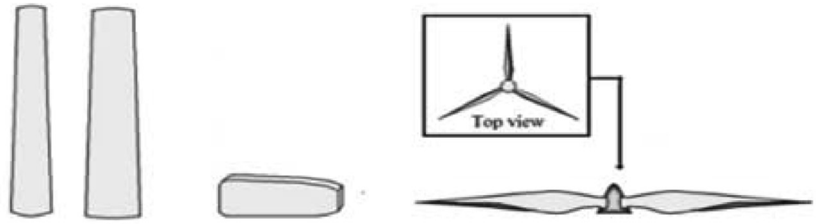

Fig. 7. "Full rotor star" composition.

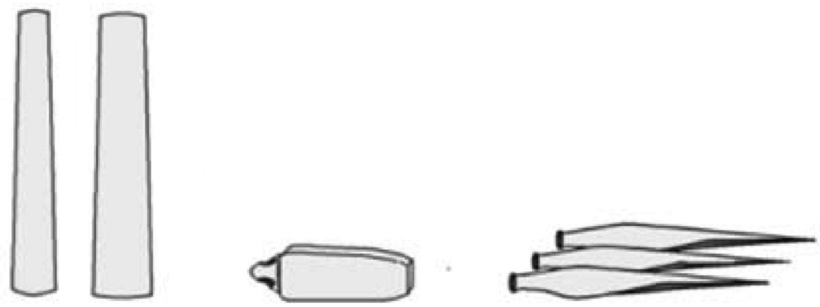

Fig. 8. "Separate parts" composition.

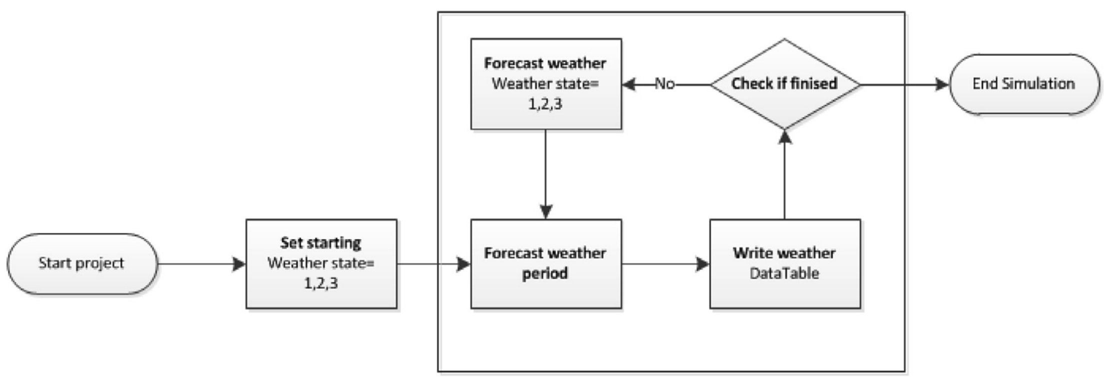

Fig. 9. Weather module.

process. The components are delayed during the given processing time depending on the loading time.

When the vessel is full (or the last turbines are ready to be shipped) the module will signal that the vessel is no longer available for loading and is ready for shipment. Hence, the shipment process can start only after the ready signal. Nevertheless, the module also needs to check if the weather forecast permits shipment. If not, the shipment process has to wait until this condition is met. All components in the vessel will then be assigned to the shipment process.

When the ship arrives at site, the components of one turbine are assigned to the jack-up buffer. Before the jack-up process can start, the module checks if the weather forecast permits jacking up. If not, the jack-up process has to wait until this condition is met. When the jack-up process is completed, the components will be assigned to the installation buffer. Before the installation process can start, the model checks if the weather forecast permits installation to proceed.

After installation is completed, the component is assigned to the return shipment buffer. The module checks whether the entire turbine is installed. If so, the jack-up process starts to lift the vessel. After all components on the vessel are installed, it will signal for the return shipment process. Again, the weather needs to permit shipment. Following that, all turbines in the return shipment process will be completed, and it will signal that the vessel is available for loading. When all turbines are installed, the process is completed.

Case study and further experiments

Real project data has been used to show the practical use of the decision-support tool that has been developed. The aim of the case study is to clearly demonstrate the features and capabilities of the DSS, and to clarify its potential use by wind turbine installation companies. In this section, first, the validation of the model, performance measurements, and output settings are discussed. Second, we will present the analysis and results for the "BARD 1" project. Third, we will present further experiments for in-depth analysis of pre-assembly strategies.

Model validation and experimental setup

Several steps were performed to validate the tool developed. First, data were gathered through multiple expert interviews and

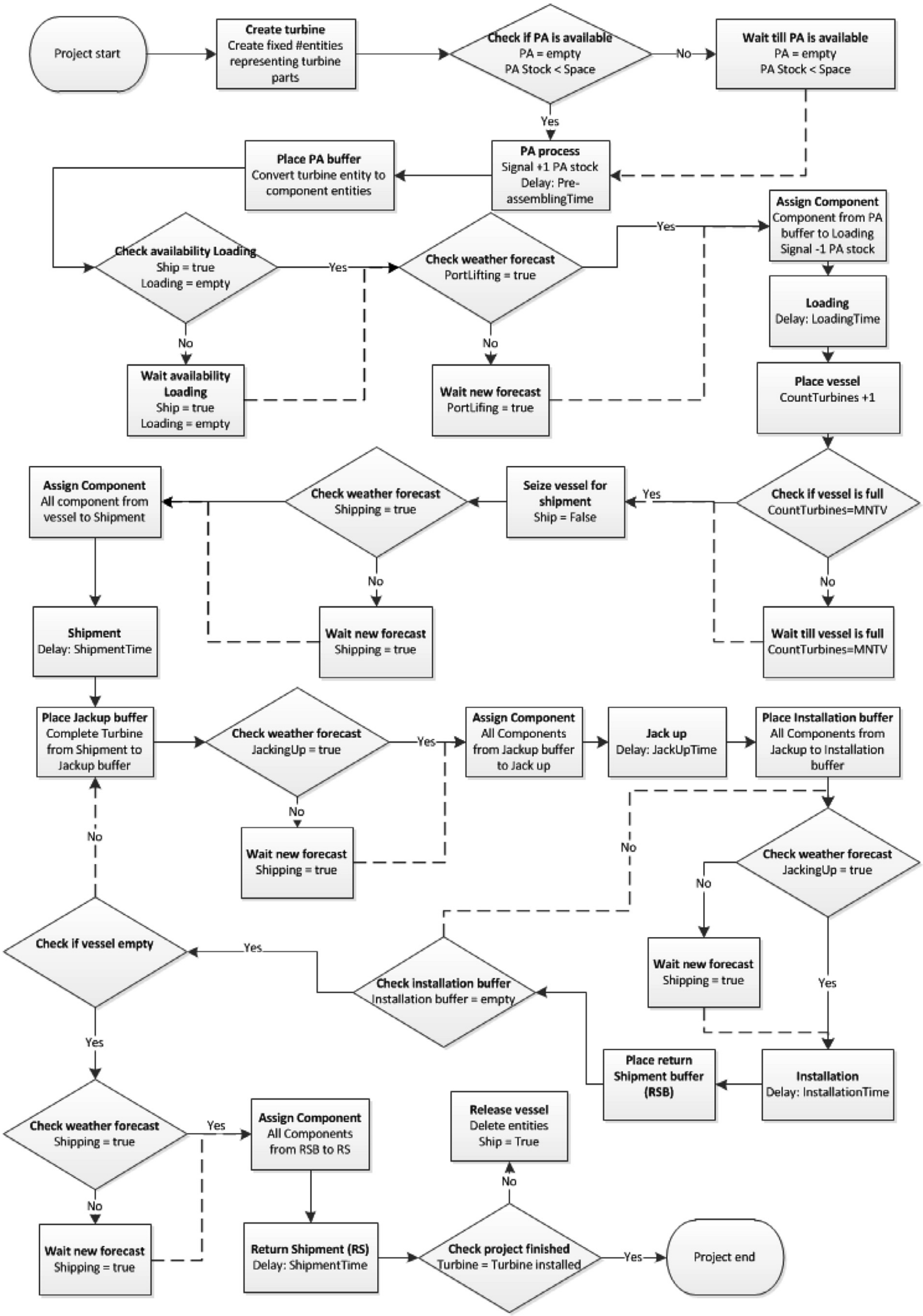

Fig. 10. Schematic overview of the installation module.

company empirical data. Following that, an extensive sensitivity analysis was performed on all input data. Validation was done through expert interviews, as well as by comparing data. In cooperation with several project leaders, the results from the model were thoroughly discussed. The conclusion was that the model was capable of assessing various logistical approaches.

As mentioned previously, the most important performance measurements for project developers are total installation time and installation cost. In practice, determining the exact installation cost is highly complex. Nevertheless, in line with the aim of the decision-support tool, determining the net cost difference between logistical methods for performing the task is what needs to be considered. *Total installation time* is defined as the actual time required to perform the installation of all turbines, and the *Net project installation cost* is the total net cost of the various costs for the different logistic strategies.

The next step is to obtain a reliable comparison between the various logistical strategies. Therefore, we need to be able to perform multiple replications for each experiment. The startup for each of the logistical methods is the same and needs to be taken into consideration within the total time. With a confidence interval of 95%, analysis showed that 30 replications were adequate for the experiments.

BARD 1

In this section, we evaluate the project ''BARD 1,'' which is located in the North Sea (Fig. 11). The offshore technicians began installation in March 2010, and installation is yet to be completed. The project comprises a total of 80 wind turbines of the type "BARD 5.0". The area is located 101 km northwest of the port of Eemshaven. The water depth at the installation site is 40 m. The port has a capacity of 60.000 m^2 and 100.000 m^2 covered and open storage area with a total quay length of 1.040 m. The port holds rail-mounted and mobile harbor cranes up to capacities of 30 t and 104 t. In addition, transport solutions are provided with 400 lorries.

In the project, several vessels were used. Because of delays, the installation phase took longer and contracts expired. New vessels needed to be contracted, because the original vessels were not available anymore. For the installation phase of the turbines, JB-115 and JB-117 type vessels were used. As mentioned in Section II, the maximum number of turbines that fit on a vessel depends on the pre-assembly method used. For the ''BARD 1" project the following data displayed Table 3 applies.

The vessels were leased. However, the contract was not made public. In 2009, SeaJacks signed contracts for the installation of wind turbines at Walney and Greater Gabbard. Effective day rates were computed by dividing the value of the contract by the number of days of operation.

For the BARD 1 project, three pre-assembly strategies, as defined in Section 2, were considered possible. Interviews with the pre-assembly company, Wagenborg, provided us with a calculation of the costs and times for each of the pre-assembly modes. Table 4 shows the given distribution of the process time in each assembly mode. It should be stressed that these figures are based on the practical experience of multiple field experts.

Three main sets of experiments were conducted separately, with a sufficient number of replications for each one. For each experiment, project performance was evaluated. Consequently, we were able to examine the performance for each pre-assembling strategy. The results showed that the bunny-ear strategy was, on average, 32 days faster than the currently used strategy, which is an improvement of 8.6%. The separate parts strategy was, on average, 100 days slower than the current strategy, which is a deterioration of almost 26%. We observed a similar pattern in terms of cost. The bunny ear was, on average, almost 4 million euros less expensive, which is an improvement of 6%. The separate parts strategy was more than 12 million euros more expensive, which represents a deterioration of 19%. The results are summarized in Tables 5 and 6.

Further experiments

Further experiments were carried out, based on discussions with the experts. The possible characteristics of the logistical methods that could influence supply-chain performance have been discussed in previous sections. The main variable in the logistical concepts is the pre-assembly strategy. The results of using different strategies were also analyzed numerically in the previous section.

One of the characteristics of the various pre-assembly methods is the number of components needing to be lifted in the loading and installation processes. A second characteristic entails the number of turbines that fit on a vessel. Based on these characteristics and the demands of project developers in the industry, the effect that the number of offshore lifts and number of turbines has on the project time is examined. To test these factors, further experiments were conducted. Total time needed to install all the turbines within different scenarios was taken as the performance measurement.

Project characteristics are also affected by the number of turbines, distance to shore, and sea depth. The depth of the sea only influences the jacking-up time. However, since this has to be done for every turbine and will be the same for all scenarios, we can observe that the sea depth will not influence the time difference between scenarios. For the number of turbines, it only becomes unbiased when all scenarios can be finished within fully efficient cycles. The vessel load varied between one and four. Calculations based on more than four turbines on a vessel were not made, since there are no vessels with such a capacity. We based our experiments on 120 turbines. The number of offshore lifts depended on the assembly strategy used, and, in practice, was found to be between four and seven. As for the distance to shore, we took a range of 85 km up to 115 km, in steps of 15 km, to see how this affected the project time.

The experiments conducted with the defined variables and the results obtained are summarized in Table 7. A control across *p*-values with a 0.05 level of significance, to see whether the difference of the mean total times of the different scenarios revealed statistically significant results, was conducted. The output numbers presented show the average number of days needed to install all 120 turbines.

For further analysis, Fig. 12 illustrates the outcome that fewer offshore lifts increase project performance. When varying the numbers of offshore lifts, we do not observe any tradeoff within different distances to shore. The minor differences we see in Fig. 12 are due to the extra shipment time.

Fig. 13 illustrates how more turbines on a vessel increase project performance. Here, we can also observe the influence of distance to shore. The greater the distance to shore, the stronger the effect that increasing maximum vessel load has on project performance.

Managerial insights and conclusion

Meeting the world's environmental challenges and ensuring economic feasibility is a major challenge. Transition to wind energy is seen as one of the most viable options for reducing humanity's ecological footprint. Together with future plans to increase the use of wind energy, developing decision-support tools will crucial support to help decision-makers make the right

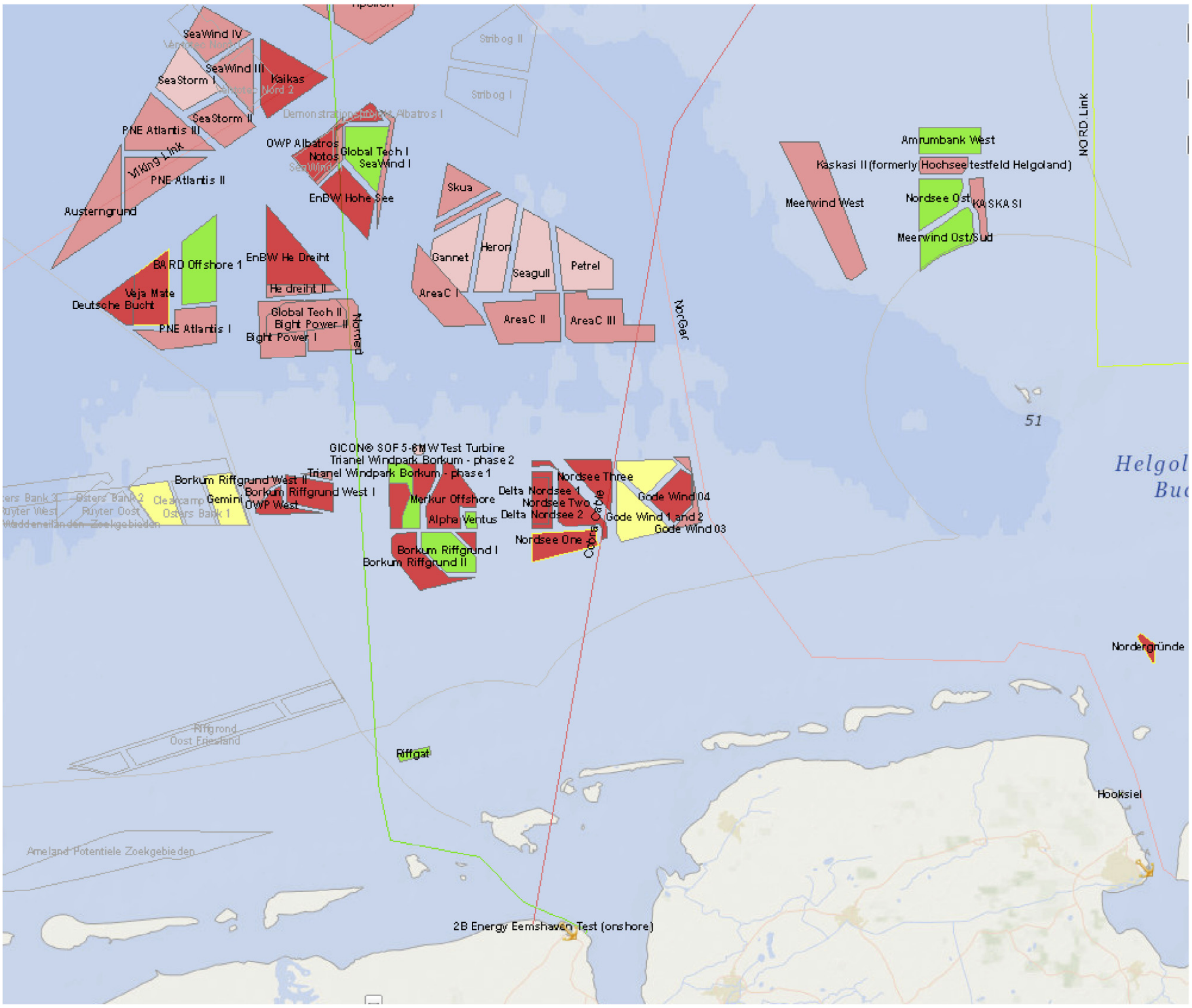

Fig. 11. Map of the BARD 1 location.

Table 3
"BARD 1" assembly characteristics.

Assembly modes	Max number of turbines on vessel	Number of lifts
Bunny ear	2	4
Full rotor star (currently used)	1	4
Separate parts	3	6

Table 4
Pre-assembly process time distributions.

Assembly modes	Pre-assembly process time
Bunny ear	$X \sim \text{Triangular}(20, 22, 24)$ hours
Full rotor star (current used)	$X \sim \text{Triangular}(15, 16, 17)$ hours
Separate parts	$X \sim \text{Triangular}(5\frac{1}{2}, 6, 6\frac{1}{2})$ hours

Table 5
Average and standard deviation of the total installation times for the "BARD 1" project.

Total installation time		
	Mean value	Standard deviation
Bunny ear	346 days 10 h	17:04:58:08
Rotor star (current)	378 days 22 h	14:19:21:30
Separate parts	476 days 16 h	17:15:14:47

Table 6
Average and standard deviation of the total net installation costs for the "BARD 1" situation.

Net project installation cost (in €)		
	Mean value	Standard deviation
Bunny ear	61,141,310.89	2,675,601
Rotor star (current)	65,045,821.08	2,292,637
Separate parts	77,640,297.34	2,749,852

logistics decisions in a highly complex environment subject to frequent disruptions.

This project is aimed at providing project planners with a decision-support tool to aid them in employing effective logistical approaches within the installation phase of offshore wind farms. To do this, we first analyzed the different logistical concepts in the installation phase of a wind farm. With current developments in the industry, the logistical approaches mainly differ in terms of pre-assembly strategy. These pre-assembly strategies have been characterized by the number of components the pre-assembly

Table 7
Average number of days needed to install all 120 turbines in the baseline situation.

		Distance to shore	Vessel load			
			1	2	3	4
Offshore lifts	4	85	548	519	503	500
		100	562	515	506	505
		115	577	522	511	507
	5	85	653	618	607	605
		100	661	628	611	605
		115	681	629	620	613
	6	85	755	729	713	709
		100	766	732	714	707
		115	775	737	722	719
	7	85	866	822	816	813
		100	871	838	815	815
		115	887	840	831	818

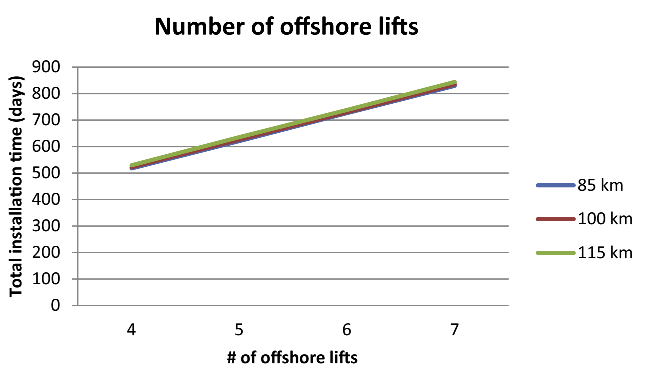

Fig. 12. Average total installation varying per offshore lifts in baseline situation.

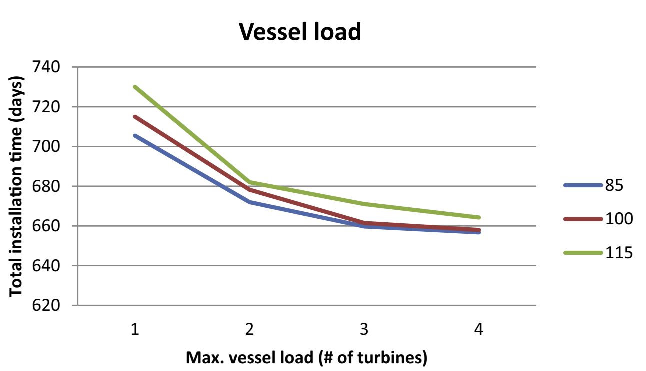

Fig. 13. Average total installation varying maximum vessel load in baseline situation.

process can handle and the number of turbines that can fit on a vessel. In addition to that, we studied the effect of the different pre-assembly strategies offshore, using the performance of a real-life wind turbine project. We observed that, in comparison to other industries, the offshore wind industry is characterized by its dependency on weather conditions. A decision-support tool based on simulation has been created, in which all the relevant logistics processes required for the turbine installations have been implemented. This system can be utilized for different project specifications and weather conditions.

Computational experiments provided valuable managerial insights into the design of logistics approaches. Accordingly, the most relevant solution depends on project specifics, which underlines the importance of assessing different settings through the use of the proposed decision-support tool. In the North Sea area, findings showed that, with a decrease in the number of components, project performance as measured in total time spent increased. This can be deduced from the fact that extra pre-assembly time is put in concurrently with the at-sea part of the supply chain. Another important characteristic is the number of turbines that can fit on a vessel. Findings reveal that when more turbines are put on a vessel, the total installation time can be decreased. Furthermore, as the distance to shore increases, the effect from increased vessel load becomes more apparent. This fact is especially important for new wind farms that are being positioned further offshore. Accordingly, we have suggested a pre-assembly strategy using a minimum number of components to be installed onsite and a maximum number of turbines on a vessel. It should be noted that in practice these are correlated, that is, when components are pre-assembled they take up more space on a vessel.

The system we have developed can be used as a tool in coming up with installation strategies for offshore wind projects. It can compare alternatives and estimate total durations for an operation, for which a schedule and budget estimates can then be developed. The study provides a blueprint to quantify monetary values for alternative scenarios. It should be noted that, as a limitation of this study, project developers may well have other, different ways of treating capital expenditures, among other investment variables.

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