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Innovative Applications of O.R.

A benders decomposition approach for solving the offshore wind farm installation planning at the North Sea

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ABSTRACT

Wind farm installation and particularly offshore wind farm installation is highly complex due to high dependency on weather and remarkably large components. Amongst others projects at North Sea face considerable interruptions due to severe weather conditions. The problem we refer to consists of determining the renting period of the offshore installation vessels and the scheduling of the operations for building the wind farm. Planners need to make these decisions under the uncertain wind states. A deterministic offshore wind turbine installation model is not suitable to capture the uncertainties which may leave the vessel resource unused or vessel being sent offshore in unfavorable conditions. Accordingly, this study proposes a model that considers disruptions arising from uncertain weather conditions which stand as the main challenge for such projects. As the compact formulation fails to provide solutions due to the large number of scenarios, an approach based on Benders decomposition is developed. The tool is applied to two major wind farm projects, “Bard 1” and “Borkum West” at the North Sea using real weather data over two years. The two-stage model leans to conservatively use the suitable conditions in advance to avoid huge waiting costs incurred under severe weather. Motivated by experts at Wagenborg and MPI Offshore, we extend our experiments to analyze cases where plants are build further away from the shore. The tool presented in this study is suitable for being used in the planning of wind farm projects providing competent solutions.

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1. Introduction

Driven by world's ever-increasing concern for sustainability, renewable energy is receiving a great deal of attention over the last decades. Limited fossil energy resources have led to the exploration of renewable energy sources such as wind and solar. Wind power is one of the greenest ways to produce vast amount of electricity with low CO₂ emissions (Diamond, 2010; Xydis, 2013; Trappey, Trappey, Liu, Lin, & Ou, 2013). Wind turbines are the most prevalent tools to convert wind energy to electricity. There are mainly two locations where a wind farm can be built. Onshore wind refers to being located on land, while offshore refers to being constructed at sea or freshwater. Offshore wind turbine (OWT) outperforms onshore on three aspects: First, the noise pollution can be avoided by being further away from citizens. Second, the limitation of machine size on the construction field can be minimized due to the larger space available at sea. Third, OWT can generate more electricity than onshore and the disturbance for wind caused by architectures nearby can be avoided (Hibbert, 2011).

The potential development of OWT is promising, but the problems are also challenging. The investment cost for the installation and maintenance of OWT is 50% higher than the onshore (Montilla-DJesus, Santos-Martin, Arnaltes, & Castronuovo, 2010). In many countries that plan for the installation of new OWTs, the projects have come to a standstill due to the extremely high investment requirements. The Netherlands is a major country with offshore wind farm installations in the North Sea where such issues have been experienced. Offshore foundations, turbines and installations are the most costly parts in the investments (Bilgili, Yasar, & Simsek, 2011). Thus, an effective and efficient way to reduce the cost becomes vital. Labor cost is related to the installation time, and the highly expensive rental cost also decreases with less rental time. With reducing the installation time, the labor cost and rental cost for installation vessels can be lowered. A better planning and scheduling activity is critical to reducing this time. Wagenborg and MPI Offshore, leading operators on the Dutch coastline, have mentioned weather as the major disturbance source. Throughout this study, two main wind farm projects in the North Sea are examined thoroughly. One of the projects, “Bard 1”, was planned to be finished in one and a half year but actually took more than three years at which weather and weather related financial issues was

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Fig. 1. Representation of top- and sub-structure of an offshore wind turbine.

one of the important reasons of delay. Hence, the need for consideration of uncertainties in weather during the planning has been stated as compulsory. Manual planning methods is currently being used for the planning problem. Accordingly, we started a project aiming to develop a tool that could be used to solve the offshore wind farm installation planning problem. In this paper, we present the model and the solution method that were developed for this purpose. The solution method has been tested on real projects based at North Sea.

The remainder of this paper is organized as follows. The second section will introduce the installation process. Related literature will be reviewed in Section 3. The OWT installation model will be presented in Section 4. Section 5 will illustrate the solution method applied to solve this model under uncertainty. Case study and computational results will be given in Section 6. The final section will conclude this paper.

2. Offshore wind farm installation problem

In the installation phase of OWT, site conditions and the operation of installation vessels are the major factors that bring challenges (Uraz, 2011). The site conditions include seabed properties and water depth. The whole offshore construction procedure is highly weather-dependent. Certain installation operations can only be carried out under suitable weather conditions. This section will introduce the processes of OWT installation and the installation vessels. Furthermore, the effect of uncertain weather conditions during the process will be explained.

2.1. OWT installation process

The installation process of OWT is mainly separated into three stages: First is the pre-assembly stage which is completed onshore. Certain components (e.g. nacelle, hub and blades) are assembled together before the construction at sea. The next stage is the installation of foundations under sea as shown in Fig. 1. All the foundations for a project need to be completed before the start of the third stage. At the third stage, turbines are divided into top and sub parts (Fig. 1) (Scholz-Reiter, Heger, Lütjen, & Schweizer, 2011). Sub structure is the tower that is placed on the foundation. Top structure including nacelle and rotor star is then installed on this sub structure. Weather has less influence on the first two stages. This study mainly concentrates on the major sections of construction that is on the planning of the third stage. Fig. 2 shows the operational processes of installation. For each vessel tour, the installation vessel is first loaded at the harbor with some separate sub and top parts. Completing that, it travels to the wind farm where the construction process begins. There are multiple processes for each vessel tour. For each building process, either one top-structure or one

Fig. 2. Operational processes of OWT installation.

subpart can be built. When all the processes have been completed, the vessel returns back and the new vessel tour begins. During the planning of operations, the decisions on how to load and when to send the vessel towards the sea in the presence of weather influence is difficult.

2.2. OWT installation vessel

The installation vessel has a key role in the installation process as it transports the pre-assembled parts from harbor to the construction site at sea (Aas, Halskau, & Wallace, 2009; Halvorsen-Weare, Fagerholt, Nonås, & Asbjørnslett, 2012; Uraz, 2011). The crane on the vessel also assists the installation. For the construction of top- and sub-structures, a Jack-up installation vessel is required. These vessels need to be rented before each vessel installation tour can start. The high-standard requirements for the cranes and infrastructure on the vessel lead to rental costs that are extremely high. Based on the project data that has been examined, the daily rental fee for a Jack-up vessel is approximately €140,000. The labor cost is also relatively high compared to labor on onshore. Consequently, substantial savings are possible with a reduced building time and better planning of vessel rental periods.

2.3. Weather effect

Previous projects confirm that weather is one of the most influential factors during installation. “Bard 1” project, as mentioned before, faced considerable delays. “Borkum West” project was initially planned to be finished in approximately 200 days while the actual service time was 367 days. Experts from both projects have underlined the weather as a major disturbance source for delays. Bilgili et al. (2011) claimed that offshore costs are greatly dependent on weather conditions. From the installation of Middelgrunden 40 MW OWT, Sørensen, Hansen, and Volund (2001) con-

Fig. 3. Operational processes of OWT installation under unexpected changes.

cluded that unexpected weather change is the major reason for project delay. Sun, Huang, and Wu (2012) also state that harsh weather is a big challenge for the safe operation during installation and maintenance. When the wind is too strong, it is dangerous to build the structures which are very sensitive to the wind speed. Since the crane on the vessel is forced to operate under unstable condition, the construction safety cannot be guaranteed (Munich, 2013).

In Fig. 2, the ideal operation process without consideration of the interference of bad weather had been shown. The process view that incorporate possible weather states are illustrated in Fig. 3. When the weather condition is unfavorable, the wind is so strong that no construction can be done. During moderate weather state, the sub-structures can still be installed; however, the practical construction time will be longer than the time that is estimated under good weather condition. Unexpected changes in weather states obviously complicate the process. Observing the first unfavorable weather block in Fig. 3 as an example, the bad weather is forecasted to begin from the sixth day and end at the seventh day. However, the situation in practice may differ, considering both the beginning date and the duration of unfavorable weather. The unfavorable/bad weather actually may begin from the eighth day of construction and end at the tenth day. These uncertainties are one of the main reasons for the delaying of the projects. Weather forecast is mainly uncertain. Therefore a deterministic offshore wind turbine installation model might not be able to capture the uncertainties which may leave the vessel resource unused or vessel being sent in unfavorable conditions. As the weather forecast becomes more reliable the problems due to such events may be reduced. However, the uncertainties will not be eliminated such that a deterministic model is sufficient. As a result, stochastic programming is used to include the uncertainties.

Next section will present the model that incorporates the characteristics of the wind farm installation.

3. Related literature

Most studies on OWT in the wind supply chain area concern production and maintenance. Only a few focus on the installation phase. Among those, Tyapin et al. (2011) compared two methods based on Markov theory and simulation to deal with weather downtime and operational time during OWT installation of a single turbine. Scholz-Reiter et al. (2011) proposed a mathematical model to schedule installation activities. This method aims at minimizing the installation time considering weather condition and operational time as constant. Accordingly, a single weather scenario is considered in the model. Ait-Alla, Quandt, and Lütjen (2013) provided an aggregate planning method for minimizing the installation cost. They provide a mathematical model which takes the capacity and weather factors into consideration. Yet again, capacity and weather condition are considered as deterministic parameters. Lütjen and Karimi (2012) presented a simulation approach for the inventory control problem during the installation process of OWT. In addition, the reactive scheduling heuristics are proposed for the installation vessels under different weather conditions. Ex-

isting models are relatively more for the maintenance and operation of offshore wind farms. Kovács, Erdős, Viharos, and Monostori (2011), Zhang et al. (2012), Besnard and Bertling (2010) focused on the maintenance of OWTs. For the daily operations of constructed OWTs, scheduling models are studied in order to minimize costs (Pappala et al., 2009; Meibom et al., 2011).

Although the consideration of uncertainty in the offshore research is not many, wide applicability of stochastic programming can be seen through its application in other industries (Herroelen & Leus, 2005; Li & Womer, 2015; Pantuso, Fagerholt, & Hvattum, 2014; Wang & Huang, 2015). Most stochastic models include demand or cost as uncertain parameters (Cardoso, Barbosa-Póvoa, & Relvas, 2013; Cerisola, Baíllo, Fernández-López, Ramos, & Gollmer, 2009; Rentizelas, Tolis, & Tatsiopoulos, 2012; Sherali, Bae, & Haouari, 2013; Velarde & Laguna, 2004). Lium, Crainic, and Wallace (2009) investigated the importance of introducing stochastic elements into service network design formulations. Santos, Ahmed, Goetschalckx, and Shapiro (2005) proposed a stochastic programming model and solution algorithm for solving supply chain network design problems of a realistic scale. Maatman, Schweigman, Ruijs, & van Der Vlerk (2002) presented a stochastic programming model to describe farmers' sequential decisions in reaction to rainfall. Huang and Ahmed (2009) addressed a general class of capacity planning problems under uncertainty, which arises, for example, in semiconductor tool purchase planning. Yen and Birge (2006) considered a stochastic crew scheduling model and devised a solution methodology for integrating disruptions in the evaluation of crew schedules. A recent work by Liu (2015) considered the problem of scheduling single-machine problems under the uncertainty of renewable energy resources. Haugen (1996) studied the planning problem of scheduling offshore gas fields and pipes under resource uncertainty. Santana-Viera, Jimenez, Jin, and Espiritu (2014) used stochastic programming to determine the capacity of wind turbine and solar panels in manufacturing companies featuring renewable energy use.

Along with the high cost of the installation phase of an offshore wind farm, more research is demanded by the industry focusing on this phase. Offshore installation industry can be characterized by its high weather dependency. Rules distinctive to the industry apply which underlines the need for developing appropriate models to support project planners. Current operations under weather uncertainty depend highly on project planner's experience. Depending on the decision maker's optimistic or pessimistic nature cases where vessels are called back or vessel is incorrectly not sent offshore is experienced. Therefore, it is important to develop a tool so that the decisions as to when and how the vessel should be sent in response to different weather forecasts can easily be made.

This paper contributes to the literature by incorporating both meteorological and operational time uncertainties reflecting the industry specific features. We approach the problem by representing the two stage decision process as in real life. In the first stage, the renting periods of the installation vessel is determined. These renting periods determine the starting time and the return time of the vessel. In the second stage decisions as to how and when to build the structures are made. Mainly, a two-stage stochastic integer program is proposed. A solution approach based on partial Benders decomposition strategy is developed to solve the planning problem of wind farms. The proposed solution is implemented using real data from two OWT installation projects "Bard 1" and "Borkum West" in the North Sea. Based on these results, conclusions and suggestions are provided.

4. The wind farm installation model

As described in the previous section, the need for a model for the offshore wind farm installation in the presence of

Fig. 4. Scenario tree generated by three weather types.

severe weather is obvious. This section introduces the mathematical model developed for the purpose. The initial model is based upon the model by Scholz-Reiter et al. (2011) and further extended to incorporate specific features such as the consideration of uncertainty. During the weather, the planner decides on the rental period of the vessel tour. The decisions as to the starting time of a tour of a vessel and the returning time of a tour of a vessel are made before the actual weather becomes known. Besides, the sailed vessels later at the offshore can find that the actual weather can fall into one of the possible weather forecasts. As a result, these vessels can delay the process or can choose among different types of operations depending on how good or bad the weather is.

Although the vessel operations are scheduled in continuous time horizon in real life, we need to discretize the time in order to have countable number of periods. Following the real life practice with respect to operational restrictions per weather class, weather is discretized into good, bad and medium in each time period to generate weather scenarios. This is also in line with current practice as decisions differ per weather classes stated here. Hence, these three different states are efficient to capture weather related uncertainty. For example, in Fig. 4 the generations of scenarios are shown for time period t to $t+1$. At time 0, we are about to make the decisions as how to send vessel into offshore. Three weather type classifications (Good, Medium, Bad) are predicted, therefore, a total of nine scenarios are generated at each time.

Departure time, top and sub structure building decisions, loading set decisions for each tour are included in our model. In line with practice, two different loading sets, representing the number of sub-structures and top-structures that can be loaded in the vessels, (loading set a and b) are considered. Indeed if required, if future practice permits, the model can be extended to incorporate further loading sets based on defined project requirements

and status. Thereafter, if the weather allows the vessel will sail to the site. After the arrival of the vessel at the offshore wind farm location with the loaded components, the installation processes can start when the weather is suitable. The model keeps track of each installation process and checks whether a sub-structure is present before a top-structure can be built. To do so the model combines the typical multi-period production formulation with a continuous job-shop formulation. The generic multi-period is useful as the formulation allows for the computation of the storage level at each time period by keeping track of the previous storage level and adding the production or subtracting demand at the current period. The downside of the formulation is the need for aggregating the production or the demand amounts to a time slot (Alumur, Nickel, Saldanha-da-Gama, & Verter, 2012; Scholz-Reiter et al., 2011; Stadler & Sahling, 2013). The typical job-shop formulation provides a more flexible approach to the start times of the operations where the start of an operation is limited to the start of the previous operation plus the duration of the operation (Chen & Luh, 2003; Gomes, Barbosa-Póvoa, & Novaes, 2013; Mao, Pan, Pang, & Chai, 2014; Scholz-Reiter et al., 2011). Combination of the two concepts, that is multi-period production and job-scheduling, is beneficial (Karimi-Nasab & Seyedhoseini, 2013) as it allows for the installation processes to be realized within the desired sequence and it also ensures that the required sub-structure is available before the installation of each top-structure.

Let, $p(\omega)$ denote the probabilities of scenarios $\omega \in \Omega$. The decision variables with ω are the extensive forms of second stage variables. The input parameters sth_t and stm_t are given with various input values together with their probabilities $p(\omega)$. Accordingly, the model for OWT installation is defined as follows:

Notation: *Indices*

$i=(1,...,V)$ Set of all vessel tours

$j=(1,...,P)$ Set of all processes at each vessel tour

$t=(1,...,T)$ Set of weather periods

Parameters

th_i	Traveling time from wind farm to harbor of vessel tour i
thl_i	Loading time at harbor plus traveling time from harbor to wind farm of vessel tour i
bts_i	Construction time for a sub-structure of vessel tour i
btt_i	Construction time for a top-structure of vessel tour i
las	Number of sub-structures in loading set a
lat	Number of top-structures in loading set a
lbs	Number of sub-structures in loading set b
lbt	Number of top-structures in loading set b
tn	Total number of turbines to be installed
sth_t	Start of bad weather in weather period t
bl_t	Length bad weather in weather period t
stm_t	Start of medium weather in weather period t
ml_t	Length of medium weather in weather period t
M	A large number

Decision variables

$sb_{i,j}(\omega)$	Start time of vessel tour i building process j under weather (ω)
vt_i	Start time of vessel tour i
rt_i	Return time of vessel tour i
$bs_{i,j}(\omega)$	1 if sub-structure is built at vessel tour i and building process j
$bt_{i,j}(\omega)$	1 if top-structure is built at vessel tour i and building process j
$as_{i,j}(\omega)$	Number of available sub-structures on which the top part can be built at vessel tour i building process j
$va_i(\omega)$	1 if vessel loading a is selected on tour i
$vb_i(\omega)$	1 if vessel loading b is selected on tour i

$wbb_{i,j,t}(\omega)$	1 if vessel tour i building process j is performed before bad weather condition stb_t
$wbm_{i,j,t}(\omega)$	1 if vessel tour i building process j is performed before medium weather condition stm_t

The aim of this project is to minimize the time of installation and the time of building. Therefore, this model aims to minimize the total return time of all the vessel tours and the total building time, which means the building phase utilizes minimum time and the vessel comes back as early as possible. This leads to the minimization of redundant time in the building phase. The idle time between processes is reduced by the formulated objective function. The formulation of the model is as follows:

Minimize

$$Z : \sum_{i=1}^V rt_i + \sum_{\omega} p(\omega) \cdot \left(\sum_{i=1}^V \sum_{j=1}^P sb_{i,j}(\omega) \right) \quad (1)$$

s.t.

$$rt_i + th_i \leq vt_{i+1}, \forall i, i \neq V \quad (2)$$

$$vt_i + thl_i \leq sb_{i,1}(\omega), \forall i, \omega \quad (3)$$

$$sb_{i,j}(\omega) + bts_i \cdot bs_{i,j}(\omega) + btt_i \cdot bt_{i,j}(\omega) \leq sb_{i,j+1}(\omega) \quad (4)$$

$$\forall i, j, \omega, j \neq P$$

$$sb_{i,j}(\omega) + bts_i \cdot bs_{i,j}(\omega) + btt_i \cdot bt_{i,j}(\omega) \leq rt_i \forall i, j, \omega \quad (5)$$

$$va_i(\omega) + vb_i(\omega) \leq 1, \forall i, \omega \quad (6)$$

$$\sum_{j=1}^P bs_{i,j}(\omega) \leq va_i(\omega) \cdot las + vb_i(\omega) \cdot lbs, \forall i, \omega \quad (7)$$

$$\sum_{j=1}^P bt_{i,j}(\omega) \leq va_i(\omega) \cdot lat + vb_i(\omega) \cdot lbt, \forall i, \omega \quad (8)$$

$$\sum_{i=1}^V \sum_{j=1}^P bs_{i,j}(\omega) = tn, \forall \omega \quad (9)$$

$$\sum_{i=1}^V \sum_{j=1}^P bt_{i,j}(\omega) = tn, \forall \omega \quad (10)$$

$$bs_{i,j}(\omega) + bt_{i,j}(\omega) \leq 1, \forall i, j, \omega \quad (11)$$

$$bs_{(1,1)}(\omega) = 1, \forall \omega \quad (12)$$

$$as_{i,j+1}(\omega) = as_{i,j}(\omega) + bs_{i,j}(\omega) - bt_{i,j}(\omega), \forall i, j, \omega, j \neq P \quad (13)$$

$$as_{i+1,1}(\omega) = as_{i,j}(\omega) + bs_{i,j}(\omega) - bt_{i,j}(\omega), \forall i, j, \omega, i \neq V \quad (14)$$

$$sb_{i,j}(\omega) + bts_i \cdot bs_{i,j}(\omega) + btt_i \cdot bt_{i,j}(\omega) \leq stb_t(\omega) + wbb_{i,j,t}(\omega) \cdot M \forall i, j, \omega \quad (15)$$

$$stb_t(\omega) + bl_t - (1 - wbb_{i,j,t}(\omega)) \cdot M \leq sb_{i,j}, \forall i, j, t, \omega \quad (16)$$

$$sb_{i,j}(\omega) - bs_{i,j}(\omega) \cdot M + btt_i \cdot bt_{i,j}(\omega) \leq stm_t + wbm_{i,j,t}(\omega) \cdot M \forall i, j, t, \omega \quad (17)$$

$$stm_t(\omega) + ml_t - (1 - wbm_{i,j,t}(\omega)) \cdot M \leq sb_{i,j}(\omega), \forall i, j, t, \omega \quad (18)$$

$$sb_{i,j}(\omega), vt_i, rt_i, as_{i,j}(\omega) \geq 0 \quad (19)$$

$$bs_{i,j}(\omega), bt_{i,j}(\omega), va_i(\omega), vb_i(\omega), wbb_{i,j,t}(\omega), wbm_{i,j,t}(\omega) \in \{0, 1\} \quad (20)$$

Constraints (2) to (5) introduce the basic operational processes of installation. After the vessel has arrived from the previous tour, it can leave the harbor for next tour. After the vessel has arrived at the wind farm, the first building process can start. Start time of every vessel tour i and process $j + 1$ must be after the start time of vessel tour i and process j plus the building time of either the sub-structure or the top-structure. When all the processes have been finished, the vessel can return. Constraints (6) to (8) are related with the loading set. Either loading set a or loading set b needs to be selected for each vessel tour. The number of sub-structures that can be built is limited by the maximum number of loaded sub-structures. This is also valid for top-structures. Constraints (9) to (12) assure that the sum of built sub-structures must be equal to the number of total turbines. This also applies for top-structures. Either a sub-structure or a top-structure can be built at each process j . For the first vessel tour, the first process must build sub structure; otherwise there is no sub-structure where the top part can be built. Constraints (13) to (14) guarantee the availability of built sub-structure. The available number of sub-structure $as_{i,j}$ is zero at the beginning and must be bigger than or equal to zero. When $as_{i,j}=0$, this process must build sub-structure. Constraints (15) to (18) deal with the interference of weather. For bad weather period, all the building processes are either finished before the bad weather or can begin after the bad condition is over. For medium weather period, only the construction of sub-structure is allowed, but it is not allowed to build the top part because the wind is too strong. All the processes can either be finished before the medium weather or begin after the medium condition is over.

In order to formulate planning solutions for OWT installation, we need to know the value of decision variables va_i and vb_i to decide which loading set to choose before the start of each vessel tour. Other important decisions are $bs_{i,j}$ and $bt_{i,j}$, that is, for each building process, whether to build top-structure or sub-structure must be decided with the aim of minimizing service time.

5. Solution approach

As shown in the previous section, a deterministic equivalent form of a stochastic program can be formulated if the uncertainties can be discretized into several possibilities along with their corresponding probabilities (Kristianto, Gunasekaran, & Jiao, 2014). However, if the number of scenarios is large, we are not able to solve the problem directly. As will be presented in the computational experiments, this issue has also been observed for the extensive form presented in Section 4. Consequently, a decomposition method is required to make the problem smaller. Benders decomposition approach has shown its efficiency within numerous application areas such as network design and location (Contreras, Cordeau, & Laporte, 2011; Costa, 2005; de Camargo, de Miranda, & Luna, 2009; M'Hallah & Al-Khamis, 2015; Osman & Baki, 2014). Accordingly, within this section, Benders based decomposition approach for solving the linear relaxations of the formulated offshore wind farm installation model will be presented (Benders, 1962). Branch and bound approach will be followed to find integer solutions.

As explained in previous sections, the OWT installation problem is a two-stage problem. In practice, project planners arrange renting contract periods for the vessels to be used in the offshore construction. This priori decision given is prone to uncertainties mainly influenced by weather conditions. Accordingly, in the proposed installation model, constraints related with variables rt_i and vt_i are built-in in the master problem. The baseline schedule is provided after this calculation. This baseline schedule determines the initial return time of vessel which in practice is to be done for arranging the renting contract period of the vessels. Given the baseline schedule, the recourse problems deal with uncertainty.

Fig. 5. Benders decomposition progress.

The decision about loading set and building decisions are made in the sub problems. At each iteration, the master problem is solved to obtain the initial value of the first-stage variables, while the second stage tackles the sub problems that incorporate uncertainties.

The progress of the Benders decomposition approach can be illustrated as in Fig. 5. The master problem is solved to attain a lower bound. Sub problem solutions will provide the upper bounds. The process will terminate when the difference between the upper and lower bounds are less than the given tolerance level. If the threshold is not reached, generated cuts will be added to the master problem and the process will continue with the updated constraint sets.

Accordingly, linear relaxations of (1) to (20) are solved by the Benders decomposition and then this solution is embedded into the branch and bound to obtain integer solutions. Benders master problem is constructed as follows: θ is introduced as the Benders cut that iterates between master problem and sub problem. Then, the objective function can be written as:

Minimize

$$\sum_{i=1}^V rt_i + \theta \quad (21)$$

$$rt_i + th_i \leq vt_{i+1} \quad \forall i, i \neq V \quad (22)$$

$$rt_i, vt_i \geq 0 \quad \forall i \quad (23)$$

$$\theta \geq 0 \quad (24)$$

Constraints (22) are retained from the original problem constraint set (2). The LP relaxations of sub problems for scenario $\omega \in \Omega$ are represented by:

(Sub problem)

$SP(\overline{rt_i}, \overline{vt_i})$: Minimize

$$\sum_{\omega} p(\omega) \cdot \left(\sum_{i=1}^V \sum_{j=1}^P sb_{i,j}(\omega) \right) \quad (25)$$

s.t.

$$sb_{i,1}(\omega) \geq \overline{vt_i} + thl_i, \quad \forall i, \omega \quad (26)$$

$$-sb_{i,j}(\omega) + sb_{i,j+1}(\omega) - bts_i \cdot bs_{i,j}(\omega) - btt_i \cdot bt_{i,j}(\omega) \geq 0, \quad \forall i, j, \omega, j \neq P \quad (27)$$

$$-sb_{i,j}(\omega) - bts_i \cdot bs_{i,j}(\omega) - btt_i \cdot bt_{i,j}(\omega) \geq -\overline{rt_i} \quad c \quad (28)$$

$$-va_i(\omega) - vb_i(\omega) \geq -1, \quad \forall i, \omega \quad (29)$$

$$-\sum_{j=1}^P bs_{i,j}(\omega) + va_i(\omega) \cdot las + vb_i(\omega) \cdot lbs \geq 0, \quad \forall i, \omega \quad (30)$$

$$-\sum_{j=1}^P bt_{i,j}(\omega) + va_i(\omega) \cdot lat + vb_i(\omega) \cdot lbt \geq 0, \quad \forall i, \omega \quad (31)$$

$$\sum_{i=1}^V \sum_{j=1}^P bs_{i,j}(\omega) = tn, \quad \forall \omega \quad (32)$$

$$\sum_{i=1}^V \sum_{j=1}^P bt_{i,j}(\omega) = tn, \quad \forall \omega \quad (33)$$

$$-bs_{i,j}(\omega) - bt_{i,j}(\omega) \geq -1, \quad \forall i, j, \omega \quad (34)$$

$$bs_{(1,1)}(\omega) = 1, \quad \forall \omega \quad (35)$$

$$as_{i,j+1}(\omega) - as_{i,j}(\omega) - bs_{i,j}(\omega) + bt_{i,j}(\omega) = 0, \quad \forall i, j, \omega, j \neq P \quad (36)$$

$$as_{i+1,1}(\omega) - as_{i,j}(\omega) - bs_{i,j}(\omega) + bt_{i,j}(\omega) = 0, \quad \forall i, \omega \quad (37)$$

$$as_{1,1}(\omega) = 0, \quad \forall \omega \quad (38)$$

$$as_{i,j}(\omega) \geq 0, \quad \forall i, j, \omega \quad (39)$$

$$-sb_{i,j}(\omega) - bts_i \cdot bs_{i,j}(\omega) - btt_i \cdot bt_{i,j}(\omega) \geq -stb_t(\omega) - wbb_{i,j,t}(\omega) \cdot M, \quad \forall i, j, t, \omega \quad (40)$$

$$sb_{i,j}(\omega) + (1 - wbb_{i,j,t}(\omega)) \cdot M \geq stb_t(\omega) + bl_t, \quad \forall i, j, t, \omega \quad (41)$$

$$-sb_{i,j}(\omega) + bs_{i,j}(\omega) \cdot M - btt_i \cdot bt_{i,j}(\omega) \geq -stm_t(\omega) - wbm_{i,j,t}(\omega) \cdot M, \quad \forall i, j, t, \omega \quad (42)$$

$$sb_{i,j}(\omega) + (1 - wbm_{i,j,t}(\omega)) \cdot M \geq stm_t(\omega) + ml_t, \quad \forall i, j, t, \omega \quad (43)$$

Constraints (26) to (43) are adapted from constraints (3) to (20). The decision variables with ω_s are the extensive forms of second stage variables. Let $\pi_{26} - \pi_{43}$ be the dual variables in relation to constraints (26) to (43). Then the cuts generated will be of the form:

$$\begin{aligned} \theta \geq & \sum_{\omega} p(\omega) \cdot \left(\sum_{i=1}^V (vt_i + thl_i) \cdot \pi_{26_i} + \sum_{i=1}^V (-rt_i) \cdot \pi_{28_{i,j}} \right. \\ & + \sum_{i=1}^V \sum_{j=1}^P \sum_{t=1}^T (-stb_t(\omega) - wbb_{i,j,t}(\omega) \cdot M) \cdot \pi_{40_{i,j,t}} \\ & + \sum_{i=1}^V \sum_{j=1}^P \sum_{t=1}^T (stb_t(\omega) + bl_t) \cdot \pi_{41_{i,j,t}} \\ & + \sum_{i=1}^V \sum_{j=1}^P \sum_{t=1}^T (-stm_t(\omega) - wbm_{i,j,t}(\omega) \cdot M) \cdot \pi_{42_{i,j,t}} \\ & \left. + \sum_{i=1}^V \sum_{j=1}^P \sum_{t=1}^T (stm_t(\omega) + ml_t) \cdot \pi_{43_{i,j,t}} \right) \end{aligned} \quad (44)$$

$$\begin{aligned} & \sum_{i=1}^V (rt_i) \cdot \pi_{28_{i,j}} - \left(\sum_{i=1}^V (vt_i + thl_i) \right) \cdot \pi_{26_i} \\ & \geq \sum_{i=1}^V \sum_{j=1}^P \sum_{t=1}^T (-stb_t(\omega) - wbb_{i,j,t}(\omega) \cdot M) \cdot \pi_{40_{i,j,t}} \\ & + \sum_{i=1}^V \sum_{j=1}^P \sum_{t=1}^T (stb_t(\omega) + bl_t) \cdot \pi_{41_{i,j,t}} \end{aligned}$$

Fig. 6. Bard 1 and Borkum West zones in the North Sea.

$$\begin{aligned}
 & + \sum_{i=1}^V \sum_{j=1}^P \sum_{t=1}^T (-stm_t(\omega) - wbm_{i,j,t}(\omega) \cdot M) \cdot \pi 42_{i,j,t} \\
 & + \sum_{i=1}^V \sum_{j=1}^P \sum_{t=1}^T (stm_t(\omega) + m_t) \cdot \pi 43_{i,j,t}
 \end{aligned} \quad (45)$$

By optimality constraints (44), θ is restricted to be larger than or equal to the optimal value of the sub problem. Feasibility constraints (45) ensure that the values given to the first stage variables lead to a bounded dual sub problem.

After solving the LP-relaxation of the problem using the above decomposition technique, traditional branch and bound approach with exact branching rules is invoked. In this technique, when integrality gaps are not too large, heuristic solutions can be followed. The work by Cordeau, Stojković, Soumis, and Desrosiers (2001) clearly describes the use of the approach.

6. Computational study and real-life cases at the North Sea

The proposed model is applied to two real wind farm projects in the North Sea: “Bard 1” and “Borkum West”. All data for the weather conditions are obtained from real data from the North Sea. Two main sets of computational experiments based on problem scale are performed. In the small-scale problems, based on expert discussions with Wagenborg and MPI Offshore, the total number of turbines to be built is fixed at 16. In this set of experiments solution structure obtained are presented. For the large-scale problems, the total number of turbines ranges from 16 to 80. These reflect the size of the examined real life projects and possible size of future larger projects. The proposed models and methods were coded in Gams 22.5. Computations are performed on a PC with AMD Phenom™ II P960 1.8 gigahertz PC running Windows 7.

6.1. Weather data

As previously stated, weather is the most decisive factor for the process of wind farm projects. The experiments are done based on the real data from the North Sea region between 2011 and 2013. Fig. 6 shows the corresponding area. This section will explain the process of generating scenarios based on the detailed analysis of

the historic weather conditions from that zone and eliciting expert’s opinions from Wagenborg and MPI Offshore.

For safety, operations are constrained by wave height and wind speed. Depending on weather forecast the lifting operations may start or the ship may sail out. Shipment of the enormous components is mostly constrained by wind speed limits. While height of waves and wind speed are correlated, wind speed limit is reached earlier. Therefore, as proposed by the experts, wind speed is the measurement used for the weather decisions. Fig. 7 shows the wind speed measurements for the “Bard 1” area in the North Sea. The wind speed data used is for times series of 1 hour over 2 years. Time series analysis of the data from the shown area does not indicate a meaningful seasonal pattern considering the wind. This also consistent with the experience of the field expert of “Bard 1” for the shown North Sea area.

It is necessary to approximate the probability distribution of the future with a finite number of scenarios. Here, discretization is made based on the characteristics of the job restrictions imposed by the weather. There are three main states of weather related with the process restrictions. Commonly, when the wind speed is below 10 meter/second lifting operations can be done (State 1). When the average wind speed is between 10 and 16 meter/second, this is regarded as ‘medium weather’ (State 2). When the average wind speed is bigger than or equal to 16 meter/second, this is regarded as bad weather (State 3) by the experts. Representing the approach followed in practice, these three different states are efficient to capture weather related uncertainty. Fig. 8 shows the probabilities of these different weather states. These limits for the weather may alter slightly from project to project. For example for the Borkum West project the limits were set as 6 meter/second for lifting operations and 12 meter/second for the building of sub structures, which eventually led to shorter weather windows.

The current state of the weather and the period length is essential for taking decisions for future operations. Accordingly, the data is analyzed to extract the length of the wind levels. Scenarios used for the experiments are built upon historical data of observations based on their frequencies. The three states of the weather condition are representing the process restrictions due the wind speed level. Shipment is possible in state 1 and state 2. Therefore, it is important to know the sequence of the weather condition levels. For example, when weather condition is in level 1 for a period of 3 hours and is followed by state 2 for a period of 3 hours, a shipment of 5 hours can be done. However if in between the weather is state 3, the shipment process may not start. Fig. 9 shows an example of how the data is interpreted. The period time for lifting is the total time the wind speed is below the limits. For example, in the first two time periods as the weather is above 16 meter/second, that is state 3, no lifting nor shipment can be done. It is however possible to perform shipment between the second and the ninth hours. Lifting operations are more sensitive to wind and on this example weather case it can only be done within the third and the sixth periods where the weather is in state 1. Making such discretization of the future state of the universe allows the expectation in constraint set (25) to be written in the form of a sum.

6.2. Small-scale wind farms

Small-scale experiments are performed to analyze the solutions and their effect on practice. The total number of turbines to be built is fixed at 16. Since the total number of wind turbines to be built (tn) is related to the number of vessel tours (V) and number of processes (P), tn is set as 16, V as 4 and P as 8. It should be noted that, in the large-scale problems, the values of tn and V should be increased according to the case scenarios. Previous section explained the distraction of the weather data. The parameters used in the experiment set is shown in Table 1. It is assumed that

Fig. 7. Hourly wind speed time series over two years.

Table 1

Input data for small-scale experiments.

Parameter	Description	Value
las	Number of sub-s in loading set a	6
lat	Number of top-s in loading set a	4
lbs	Number of sub-s in loading set b	4
lbt	Number of top-s in loading set b	6
th_i	Traveling time from wind farm to harbor of vessel tour i in days	0.1875
thl_i	Traveling time plus loading time from harbor to wind farm of vessel tour i in days	0.3333
bts_i	Building time for sub-structure of vessel tour i in days	1
btt_i	Building time for top-structure of vessel tour i in day	2

Fig. 8. Weather state probabilities for Bard 1.

Fig. 9. Example weather data analysis for Bard 1.

we use the same vessel type for every vessel tour hence we keep the travelling and building times similar for each tour.

We have initially solved our case using the extensive compact formulation given in Section 3 (Constraint sets 1–20). The case problem has 14,266 rows and 1169 columns with 12 weather periods. We were unable to have an optimal solution due to the lack of memory to store the tree. Thereon we continued our experiments using the decomposed method. Fig. 10 illustrates the solution structure from the weather influenced model obtained by the proposed Benders-based decomposition approach. At the start of each vessel tour, decisions about loading set choice must be made. At each vessel tour the vessel can choose from loading six sub-structures and four top-structures or six sub-structures and four top-structures. In the figure we show the process order of the first two tours. Loading sets b are chosen for these first two tours. Installation starts with the loading of loading set b . The vessel then sails to the site and can start with the building of the first sub-structure. Note that the first process has to be a sub-structure as top structures can only be installed upon the already installed sub-structures. At each process this check needs to be done. The second process within the first tour is again the building of a sub-structure. After the installation of the second sub-structure the processes must be halted due to unsuitable weather. When the weather limit is below 10 meter/second and the weather window is sufficient enough a top structure can be built. Process three is the building of a top which is then followed by a sub-structure installation. The operations must again come to a halt due to unfavorable weather before another substructure can be built in process five. Wind speed limit must be below 16 meter/second for a sub-structure to be built. The first tour is completed with the further building of three more top structures. The vessel then returns back to harbor. The second tour starts with the loading of the loading set b . In case components are not able to be installed due to weather conditions they can be carried on to the next tour. We can also observe the impact of the weather in the second tour as the processes are halted several times due to unfavorable weather.

It can be noticed that the result gives a flexible solution that suggests some top-structures to be finished before the sub parts. Processing operations with higher flexibility obeying weather

Fig. 10. Solution structure for two vessel tours.

restrictions provides better opportunities for reducing the service time.

6.3. Projects at North Sea and what-if scenario analyses

The new sets of experiments presented in this section are based on real life case data and future possible states of wind farms. Namely, expert interviews and operational data from the “Bard 1” and Borkum West projects have been utilized for in-depth analysis of the problem.

The windfarms consisted of 5 Megawatts turbines, featuring a 122-meter rotor diameter, with a box-type nacelle which is 14 meter-long, 8.5 meters wide and 8 meters high. As is common to most offshore wind turbines, the components of the turbines are: the tower, nacelle, hub, and three blades. For both the projects, “full rotor star” installation technique was used. In this technique the hub and the three blades are assembled at the port shaping the complete rotor. Tower sections and nacelle are placed separately on the same vessel. A turbine is transported to the site in four pieces and requires four offshore lifts at the construction site.

The offshore site is supported from the port in Eemshaven which is located 101 kilometers north-west (see Fig. 6). The water depth at the installation site is 40 meter. The port has a capacity of 60,000 meter² and 100,000 meter² covered and open storage area with a total quay length of 1,040 meter. Rail-mounted and mobile harbor cranes up to capacities of 30 t and 104 t serve within the port for the lifting operations. Transport solutions are provided with 400 lorries.

The model is executed with a time limit of two hours with data using these two projects. Of the two real life projects, “Bard 1” project comprised of 80 turbines while “Borkum West” completed 40 turbines in the North Sea. Weather data from the region are used as input. Section 6.1 explains the process for the analysis of the region’s weather. The weather limits for Bard 1 is 10 and 16 meter/second for top and sub structures, respectively. For the Borkum project the weather thresholds are tighter: 6 and 12 meter/second.

Bard 1 project used two vessels throughout the project: First JB-115 and concurrently JB-117 from Jack-Up Barge. The vessel is capable of carrying a full rotor star turbine requiring 4 lifts at the site. In the “Borkum West” project MPI Adventure from MPI/Vroon is used. The vessel can sail to the site in approximately 4.5 hours and in total 3.5 hours is needed to load the vessel. In case, the weather does not allow for installation at the site, she can sail back and be

Fig. 11. Computational performance with different solvers.

replenished with a complete complement of components for the next tour. The building of a sub structure takes approximately 24 working hours, whereas double the working hours are required for the top structures. Indeed, the installation may be delayed considerably due to high wind and insufficient weather windows.

With these given case inputs, we solved the two-stage stochastic program solved with decomposition. Initially, for practical purposes we experimented different solvers and parameters to choose the setting that best fits for our problem. Fig. 11 depicts the execution time in seconds for the different cases using different solvers, namely CPLEX 12.6.2, Gurobi 6.0.5 and Xpress 28.01. Although the performance of the three solvers were closely aligned for the first three instances CPLEX showed slightly better computational performance for the larger experimented instances. Accordingly we continue our experiments using CPLEX. Table 2 presents the detailed results for each case solved with this solver. The columns list the different cases examined. Note that Borkum West-A and Borkum West-B is given to differentiate between different weather thresholds applied. Borkum West-A uses the thresholds as 10 and 16 meter/second for top and sub structures whereas Borkum West-B sets these as 6 and 12 meter/second. The first row shows the periods that the vessels are scheduled to operate. The second row gives the number of turbines to be built throughout the project. The third and the fourth rows include the number of columns and rows in this specific example for the extensive formulation. We then report the total number of iterations performed. We provide the cost of the LP relaxation of the problem, the cost of the integer solution and the gap between the costs. We also report the total time spent in solving the LP relaxation of the problem and the total CPU time. The last row indicates the total service time. It should be noted that huge number of scenarios lead to longer computational times. The number of columns and rows grow

Table 2
Computational results for real life case data inputs.

	Small-scale	Borkum West-A	Borkum West-B	Bard 1
Weather periods involved	1–12	1–36	1–36	1–60
Number of turbines	16	40	40	80
Number of columns	1166	8113	8113	21,201
Number of rows	14,266	125,738	125,738	347,778
Iterations	173	382	231	688
Z_{LP}	1428	8230	10,067	12,429
Z_{IP}	1464	8272	10,090	12,472
Gap (%)	0.2	0.5068	0.2279	0.3417
CPU LP(sec)	4.125	8.547	6.125	42.422
CPU Total (sec)	5.476	21.341	19.735	274.546
Total service time (days)	83.185	169	232	279.521

proportionally as the number of scenarios increase, which is due to the length of periods involved. This can easily be observed in the Bard 1 instance where the total time required to solve the instance increases with the extensively growing number of scenarios. The effect of different policies on weather thresholds can be observed by looking at the cases Borkum West A and Borkum West B. For the Borkum West A we show the results for the weather thresholds used in Bard 1 project. Borkum West B is the results for the real practice threshold used for this specific case. Namely, lower wind limits were set for the project and we can observe that this can have an effect of extending the project duration of around 2 months. As can be seen from the table, the LP relaxation yields fairly good lower bounds. However, the continuous solution for example allocates fractional values for the decisions to build top or sub structures (variables $(bs_{i,j}(\omega), bt_{i,j}(\omega))$) which is not doable in practice. We have exploited the problem structure considering the stochastic aspects as follows: For branching, variables corresponding to the $\omega \in \text{argmax}_{\omega} \{p_{\omega}\}$ are considered first. This is motivated from the fact that we should focus on highly probable scenarios first as feasible solutions since these provide useful insights into the solution process (Parija, Ahmed, & King, 2004). Moreover, for a given scenario ω the sets of variables corresponding to the earlier time periods is given the branching priority. This is due to the fact that variables appearing in the earlier stages affect the feasibility of the latter ones to help cut down the solution space. We have also tightened the big-M coefficients in (41) and (42) to the maximum values of the unsuitable weather windows, starting of weather state and the duration for the bad and medium weathers, respectively. Work by Parija et al. (2004) provides an excellent reference to the techniques that can be employed to exploit the problem structure of such stochastic integer programs.

The detailed analysis of the solutions for the cases structures the strategy of the decisions given under the two-stage model. It is of interest to note that combined building strategy of top and sub structures when the limitations permit is suggested. The two-stage model leans to conservatively use the suitable conditions in advance to avoid huge waiting costs incurred under severe weather. Such analyses as the ones shown here may be very useful for planning the order of the operations if for example the planners agree to simultaneously build top and sub structures for the different turbines. In such cases, substantial cost savings may be attained.

We may now look closer into the analysis of the realm of the two projects to attain a better grasp of what the method proposed here can provide and also to have a better understanding of the factors that affect the installation of wind farm projects.

For the “Bard 1”, the offshore installation started in March 2010 and it took more than three years to be completed. The project had run into many setbacks and cost overruns which included political, technical and financial difficulties which all substantially delayed the project. Initially a JB-115 type vessel was contracted. With the

delays, the contract had come to an end and subsequently JB-117 type vessel was later used from Jack-up Barge.

Based on the model the installation excluding the financial and political related problems and including the foundations would take approximately 500 days. Together with the cable laying job this approximates the initial plans of the one and a half year duration. The wind farm officially inaugurated in August, 2013. However it had to be shut down due to several major technical problems. The future of the windfarm is currently unclear mainly arising from the technical problems in transmitting the energy to onshore. The external problems were indeed so severe also leading to bankrupt which indicates that the fate of the wind farms lies under many different factors.

The installation vessel “MPI Adventure” was rented for the “Borkum West” project. The whole project lasted for 367 days. Note that, due to technical differences and policies, the weather state thresholds were different from the Bard 1 project. Borkum West followed stricter thresholds which resulted in shorter weather windows and longer installation times. Indeed we may see the effect of the weather thresholds used in the two results provided in Table 2. The effect can be as much as 2 months for the considered area. Note that the results given in the table gives the duration for the installation of the top and the sub structures.

An important aspect to note is that the Borkum West project was initially planned by MPI to be finished in 200 days. The project duration was instead 367 days where the main factor for delay was stated as weather. The model we propose here gives an estimation of 232 days excluding the foundations. The installation of the foundations and pre-assembly also accounts for the total project duration which is approximated as 120 days. Accordingly we may say that the model would give an estimate of 352 days for the project duration which is more realistic than the 6 months base-line plan. Based on these, we can say that the model estimates the practice more accurate than the initial plans done traditionally. It is also of major interest to give indications on the economic aspects of the project. This will give an insight into the gains that can be attained by a more accurate plan that considers uncertainty in weather. An installation vessel requires a substantial amount of an investment. Financing these vessels becomes quite an issue. The most common financing method for a vessel is leasing it 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. For the cases we present here experts approximates the day rate as €140,000. It is important to note that these vessels are specially built vessels and their availability is also an issue. Planners want to estimate their rental periods as accurately as possible since short renting periods may end up with the unavailability of the vessel and long rental periods may cause extra economic burdens. A more realistic consideration of weather related uncertainties is indeed then important as the consequences of the errors is significant. Other than the

Fig. 12. Total service time vs. vessel load and distance to shore.

vessel renting costs, cost of the loading, shipment and installation are mainly driven by labor cost. It should be emphasized that the labor cost for installation at offshore is considerably higher than the onshore. Considering the cases we analyzed we may conclude that offshore installation operating costs are indeed high and it is important to have schedules that are more realistic to prevent additional charges.

We have further discussed our results with Wagenborg business development manager and MPI offshore site manager. Another important point of interest noted is the analysis of distance of the wind farm to the shore and the vessel load. This interest is mainly due to new wind farms being built further away from the shore. The vessel load on the other hand is linked to the vessel size, which is linked to the vessel day rate. Considering the high vessel rates the effect on service times is indeed significant for the planning purposes. The model proposed in this research is suitable for use as an aid in decision making for these purposes. Accordingly, for our new set of experiments we took a range of 85 kilometer till 115 kilometer in steps of 15 kilometer assuming a fixed sailing speed to observe the effect on service time. The vessel load set is varied between carrying a single and four wind turbines. For the future situation project we experimented for 120 turbines. Fig. 12 shows that more turbines on a vessel decrease the total service time. However, we also see the influence of distance to shore. The more distance to shore, the stronger the effect of increasing maximum vessel load has on project performance. This fact is especially important with new wind farms being positioned further offshore from land. Accordingly, we suggest a pre-assembling strategy with a minimum amount of components to be installed onsite and 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 more space on a vessel.

7. Conclusions

Wind power industry is one of the most important renewable energy sources. The market is expected to continue growing for the next decades. Future installations of wind farms will be more and more shifted towards offshore as the generation potential in the land side is limited. Offshore has advantages compared to onshore, such as high potential of the wind energy above the sea, less visual disturbance, and large availability of space that allow implementing projects on larger scale. However, offshore wind projects are on average three times more expensive than onshore wind projects of the same nominal power. This is due to the fact that installation at sea is much more difficult and necessary equipment is very expensive. For the projects observed at the North Sea the daily vessel rental cost alone may reach to 140,000 euros. Bard 1 and Borkum West lasted for approximately 3 years and 1 year respectively.

A major problem that offshore wind projects are struggling with is planning. Execution of nautical operations obliges that a number of circumstances concerning the weather and sea state are satisfied. These conditions may differ from project to project based technical specifications and installation policies. For example, top structure building operations at Bard 1 was limited to a wind speed of 10 meter/second. Borkum West restricted this to 6 meter/second. Experiments we provide show the magnitude of the impact on the different policies employed. This can indeed affect a project's duration by a couple of months.

Due to uncertainty in weather, the time interval when operations can be performed is usually difficult to predict. This is largely because planning takes place over time periods where the weather forecasts no longer can be relied upon. For example, for the Borkum West project the installation of a complete top side of the wind turbine generator that MPI achieved was 25 hours yet some wind turbine generators were under construction for over 3 weeks due to weather conditions. The renting periods for the vessels should be determined beforehand and these costs are substantially high. The installation of the first wind power projects are delayed considerably which led to extra costs. The influence of restricted time windows by weather conditions for the installation of wind turbines at sea was underestimated which led to financial instabilities. Therefore, it is of crucial importance to provide tools for project planners that considers disturbances faced in the installation of wind farm projects and increase the probability of effective implementation preceding the beginning of the operations.

Accordingly, this study proposes a model for the wind farm installation under uncertain meteorological conditions. The model's features and capabilities are discussed with Wagenborg and MPI Offshore which makes the model a good representation of real life applications. Weather related disturbances on the specific operations within the installation process are thoroughly analyzed and represented for the Bard 1 and Borkum West projects. Benders decomposition based solution approach is developed for solving instances of these two real life cases at the North Sea. To do so we have studied the weather and wind conditions at the North Sea for over two years. Analysis of real data and model results indicates the potential of providing better planning tools and reducing the instability and the vessel return time and building time of wind farm installation projects. The model relies on the use of more representative weather data considering the uncertainties. More realistic planning tools are of high value in the offshore sector as the costs are considerably high solely considering the vessel rental rates. We have shown through comparisons with typical planning that the model is able to propose more accurate plans. The study has shown to be very valuable by the planners at Wagenborg and MPI Offshore.

It should be noted the use of the model can further be extended to use as a shorter term decision support tool. In such cases by then available more accurate weather forecast data can be input into the model to schedule the different operations that can be done at the site. Although, decisions as to the renting period of the vessels generally is done prior to the availability of a rather accurate weather forecast, the tool can still be used to align the operations at the site.

It is hoped that this study will further attract the attention of researchers where the need for further research is apparent based on the challenges present and upcoming installations of new wind farms.

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