Planning and control of logistics for offshore wind farms

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Abstract: Construction and utilization of offshore wind farms will increase within the next years. So far the first German offshore wind farm was constructed and put into operation by “Alpha Ventus”. Experiences illustrate that bad weather conditions are the main cause for delays in transport, handling and installation of offshore wind farms. This can lead to extensive project delays of several months. The main objective of current logistical research activities is the robust design of planning and control methods for offshore installations. In this study, the basic conditions and existing disturbances of supply chains for offshore installations are analyzed. Based on these results, a planning and control concept will be introduced. Additionally, a mathematical model using mixed integer linear programming (MILP) is developed. It calculates the optimal installation schedule for offshore wind farms by observing different weather conditions. The model can be used to reduce vessel operation times in dependence on seasonal or up-to-date weather forecasts.

Key-Words: - Maritime Logistics, Supply Chain, MILP, Installation Scheduling, Offshore Wind Farm

1 Introduction
The supply of fossil energies as coal, oil and gas is naturally limited in Germany and the utilization of nuclear energy is politically restricted. On consequence, the utilization of regenerative energy supplies like water, sun and wind is publicly funded. After the installation of more than 20,000 wind turbines onshore in Germany until the end of the year 2009, the first German offshore wind farm “Alpha Ventus” was opened in April 2010. Other European countries such as England, Denmark or Sweden, own bigger experiences with the installation of wind farms, which were documented in reports published in [1,2,3]. Beside enormous technical challenges with the components of offshore wind turbines, the logistic is also demanded to develop efficient installation and material supply concepts for the offshore-wind farms. Up to 2020 the installation of more than 37,000 MW [4] is planned in Europe, what corresponds to an annual installation of more than 1,000 offshore-wind turbines. On account of this scale the establishment of standard processes for logistics is necessary. They should consider planning aspects as well as execution aspects and should allow an efficient schedule of restricted resources like e.g. installation vessels and port facilities.

First, we present aspects of the installation of offshore wind turbines. We describe different installation scenarios and the resulting requirements for the installation vessels. In a further step, the challenges of the supply chain management are discussed and occurring problems analyzed. Besides, we look at the weather forecasts and examples of offshore planning systems, which try to deal with these. After that, we present our own concept of a planning system for the installation scheduling of offshore wind farms. Following the mathematical model is introduced and an exemplary optimal installation schedule is calculated. After all, we conclude and provide an outlook to our next activities.

2 Installation of offshore wind turbines
The installation of offshore wind turbines (OWT) is influenced decisively by the weather. While foundation structures can still be installed with greater airflow conditions and wind force, nacelle and blades require still air. In particular, the assembly of the blades requires nearly calm state. The feasibility of a wind farm construction is very low concerning the servicing and repair operations. For example, it is estimated by 50% to 75% in a year for a wind farm close to Ireland [5]. This leads to an extreme stockpiling of material and resources in order to exploit good weather periods for intensive installation or servicing work. This concerns the components of OWTs, which must be held ready in the harbor or on the vessel, as well as personnel capacities, which are needed for the installation processes. In addition, vessel and handling capacities are bounded to the harbor.

2.1 Installation scenarios and vessel requirements
The installation scheduling of offshore wind farms is dependent strongly on the current weather conditions on
sea. Accordingly, different attempts exist which offer options for an optimized scheduling. It can be distinguished between three installation scenarios \cite{4}. As shown in figure 1, the first option (a) includes the preassembly in a closer situated harbor. Because of the shorter transport time to the wind farm, quick reactions to weather changes are possible.

![Figure 1: Installation scenarios: a) The components, produced by a manufacturer (M) are transported to the assembly port (P) and assembled there. They are brought to the construction at the wind farm (WF) afterwards, b) the components are transported from manufacturer (M) near to the wind farm (WF). A ferry traffic is used to transport the components over the last stretch c) the components are directly transported from manufacturer (M) to the construction at the wind farm (WF)](image)

The second option (b) contains the assembly at the establishment place. It occurs through so-called construction vessels or platforms, which are supplied by mostly smaller supplier vessels with suitable components and material.

By the third option (c), pre-installed single components are brought directly by the supplier assisting quick "Jack-up" vessels to the construction sites. They are mounted there by integrated vessel cranes. The "Jack-up" shows a mobile lifting platform, which can stand with the help of lowerable main pillars on the seabed. Therefore, the necessary stability is guaranteed for the assembly process. Figure 2 shows the concept of such an installation vessel, which is designed to operate in medium water depth of 30 to 40m. These vessels operate on its own and transport also the OWT-components. In comparison to other vessel types, they should be able to extend their operation time by 50 percent to more than 260 days per year.

![Figure 2: Offshore installation vessel with jack-ups (Beluga-Hochtief)](image)

Additionally, they will be able to operate with different loading sets. Depending on project status and weather condition the loading set will be varied. In times of bad weather, the loading set will consist of substructures, which can be installed also with higher wind forces and waves. Good weather conditions will increase the amount of nacelles and blades, which will be loaded. At the moment, the offshore companies plan to install substructures in the darker months from autumn to spring and to assemble the nacelles and blades in summer. Because of the seasonal weather changes, this should help to get a high utilization for the installation vessels. The idea of this paper is to present a method, which allows a dynamical installation planning of shorter time periods on the basis of up-to-date weather forecasts. This means that optimized loading sets, installation sequences and material demands will be calculated.

2.2 Challenges in planning of offshore supply chains

Regarding the offshore material demand, the whole supply chain must be flexibly organized in order to a fast reaction to disturbances. Especially by fine weathers, massive material requirements are needed in a short time that must be mapped into the supply chain. On this occasion, inventory stock, production and delivery times must be synchronized, so that the installation of the wind farm is not delayed by material shortages. The main challenge is the correct determination of the inventory targets in the harbor. Under inclusion of the restricted harbor facilities and economic considerations, the inventory targets must be defined in a way that a continuous supply with OWT-components is guaranteed.
Outgoing from the inventory targets in the harbor, the whole supply chain can be organized with concepts from the automobile industry. The supply chains in the automobile industry are state of the art and very efficient and flexible.

Especially for the growing number of OWT-installations in the next 10 years, it will be necessary to get well functioning supply chains, which allows a line production of wind farms. The high process transparence, which is e.g. known from the automobile industry, will be also important for the offshore assembly. Process disturbances in transport or manufacturing lead to high subsequent costs, because the installation vessel has to return to the harbor. To avoid process disturbances, all aspects, which are able to affect the supply chain, must be analyzed at first. In figure 3, the material flow process from the production up to the offshore installation is illustrated and the respective possible disturbance variables are identified.

![Figure 3: The material flow process and its disturbance variables in the supply chain for the installation of offshore wind farms](image)

Between production and offshore installation, it exists the shore-based transport, handling at the harbor and the sea-based transport. The disturbances can reach from capacity problems over quality problems to different traffic and weather conditions. As a result, we have to deal with delays in the supply chain. In order to increase the transparence and the application of robust planning and control methods we have to use information technologies for tracking and tracing.

### 2.3 Weather forecasts

In order to include weather conditions into the installation planning of offshore wind turbines, weather forecasts are essential. Weather predictions and numerical weather forecasts can be calculated with different models. Reliable weather predictions are mostly provided for a period of approx. 14 days. With the assistance of ensembles such predictions are validated while in the so-called main run the real weather data are illustrated and easily varied data are processed in other runs of it. If the runs are very similar, it is very likely that the prediction is reliable [6]. Beyond that, seasonal weather forecasts exist. They are applied long-term and are valid for longer periods e.g. months. Such forecasts are based on historical data and give ideas such as average wind speeds, temperatures and rain falls in this periods. Based on these long-term forecasts, it can be predicted that in winter the probability of days with good weather conditions is significantly less than in summer. Therefore, the master plan of the offshore companies is to install the sub-structures in the darker months and the top-structures like e.g. tower, nacelles and blades in the summer time. However, experiences of wind farm installations show that this is not that easy. An integrated planning of the installation of sub- and top-structures by considering short time forecasts is necessary in order to get an optimal utilization of the vessels as limited and expensive resources.

### 2.4 Examples of planning systems considering the weather relations

A suitable planning model for the installation of offshore equipments has not been introduced in the literature up to now. The topical software solutions are aimed only on the operation of wind farms or equipments. The ITS IT service Salzgitter GmbH owns with WindPLANT a software, which serves for the technical operation of wind farms and owns an expansion module for the weather-conditioned maintenance planning. Another manufacturer of corresponding operating software is the BTC Business Technology Consulting AG. With BTC wind farm centre it disposes a product solution that supports the technical manager in execution and documentation of the necessary maintenance and servicing measures [7]. Finally, it can be noticed that no logistical oriented software solution could be identified for the assembly of offshore wind turbines, which takes the weather effects into consideration. The introduced research approaches offer valuable approaches for the development of specific offshore solutions. However, they are not transferable on account of the restrictions specific for application.
3 Concept of a planning system for the installation scheduling of offshore wind farms

The objective of a planning system for the installation of offshore wind farms is to reduce the construction time, which is proportional to the installation costs. The capacities of vessels, harbor facilities and staff have to be chartered for the planned project time and each additional day leads to extra costs. Therefore, the concept of the planning system concentrates on the offshore activities by developing a MILP planning model, which contains transport and installation processes, different weather conditions and an installation vessel as resources (figure 4).

Additionally, in the near future vessels will become the bottleneck in the wind farm installation process [4]. Therefore, it is important to optimize especially this part of the supply chain.

4 MILP for vessel planning

As mentioned above we developed a mathematical model using MILP to calculate optimal installation schedules for the vessels. Installation vessels are already the bottleneck in wind farm installation processes and they probably will stay. Their utilization should be as high as possible and they should be used in the most efficient way. The general objective is to minimize the building time for a wind farm. The developed model can not only be used for exact short-term planning, it is also applicable to simulation runs calculating project durations regarding different weather seasons in long-term planning.

4.1 Properties of the mathematical model

The following properties of the installation processes are considered in model:

1. One installation vessel for the installation of one wind farm
2. Selection of a loading set at the harbor (how many sub-structures and how many top-structures can be loaded)
3. Vessel loading time and travel time from the harbor to the wind farm and back
4. Building time for a sub-structure / top-structure
5. Weather conditions are modeled in three types
   a. good weather: substructures and top-structures can be built
   b. medium weather conditions: only substructures can be built
   c. bad weather conditions: nothing can be built

The input parameters for our model are shown in table 1.

<table>
<thead>
<tr>
<th>Input parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of wind turbine installations</td>
<td>12</td>
</tr>
<tr>
<td>Vessel loading time</td>
<td>8</td>
</tr>
<tr>
<td>Vessel travel time to/from wind farm</td>
<td>4</td>
</tr>
<tr>
<td>Sub-structure installation time</td>
<td>24</td>
</tr>
<tr>
<td>Top-structure installation time</td>
<td>48</td>
</tr>
<tr>
<td>Medium weather start times</td>
<td>Array of weather start times</td>
</tr>
<tr>
<td>Medium weather durations</td>
<td>Array of weather condition durations</td>
</tr>
<tr>
<td>Bad weather start times</td>
<td>Array of weather start times</td>
</tr>
<tr>
<td>Bad weather durations</td>
<td>Array of weather condition durations</td>
</tr>
</tbody>
</table>

Table 1: Input Parameter

The model can be easily extended especially for more detailed installation steps and components. Just the same, with weather types, which can be adjusted to the installation steps.
In figure 5 the sequence of the installation steps is depicted. At first, the vessel loading set is selected. The installation ships can handle with several fix loading sets because each set requires their own superstructures on ship. Currently the model supports two loading sets: the first contains 4 sub-structures and 2 top-structures and the second contains 2 sub-structures and 4 top-structures. After the loaded vessel is arrived at the wind farm, the installation processes can begin, if the weather conditions allow it. Each installation process is indexed, which allows the solver to check at the beginning of the top-structure installation process, if there is at least one sub-structure available. To do this, the model combines the typical multi-periodic production formulation (e.g. [10]) with the typical continuous-time representation of a job-shop (e.g. [11]). The multi-periodic formulation sets the current storage level to the storage level from the last period plus the production minus the demand. The advantage of this model technique is that the discrete storage level is known at each period. The disadvantage is, that there is always a discrete time slot and for example production amounts can only be set for a whole period (s_i : storage; p_i : production; d_i : demand; t : period):

\[ s_i = s_{i-1} + p_{i-1} - d_{i-1} \tag{1} \]

The job-shop formulation is more flexible with, for example, start times, because the model only defines that the start time of production \( x \) starts after production \( x-1 \) plus the duration of the production (pt):

\[ x_{i+1} \geq x_i + pt \tag{2} \]

The model also checks the availability of required structures on ship for each production step. Installation times are non-overlapping with weather conditions. Only sub-structures can be built during medium weather.

### 4.2 Complexity and Solver runtime

The planning problem belongs to the NP-hard problems, but since the planning model considers only one vessel, realistic scenarios can be calculated in acceptable time. SCIP [12] was able to calculate an optimal solution for the example provided in 4.3 in less than one minute on a standard office computer. However, adding more wind turbines or weather types leads to a much longer solving time or makes the model unsolvable. On the other hand, model optimization [13] could increase these numbers again.

### 4.3 Planning and scheduling example

Since weather forecasts are only valid and useable for a short time horizon, the Solver (e.g. SCIP or CPLEX) should solve the mathematical model each time the vessel arrives at the harbor and needs to be loaded. This way the current weather conditions can be integrated into the planning most reliable. To optimize the supply chain and make sure that parts of the wind turbines are ready for the vessel, longer planning horizons should be considered. An example of one wind farm with 12 turbines is provided here. Additionally to the data presented in table 1 weather periods have been added randomly. Periods are usually 1-3 days long and might be overlapping. The probability of medium weather and bad weather are approximately 33% each. That means, that each condition, good weather, medium weather and bad weather, equally occur. A Gantt chart of the example data is presented in figure 6. Loading sets correspond to the number of sub- and top-structures.

### 4.4 Simulations with stochastic weather conditions

The MILP can be used for simulation runs considering ‘stochastic’ weather conditions. One might be interested in estimates of the building time of a whole wind farm: good estimates, which can be used for supply chain optimizations later, can be calculated by simulating different weather conditions and their (partly faulty) forecasts. The MILP is solved exactly for each weather and forecast combination. Moreover, if enough simulations runs are performed, significant statistical results can be gathered.

### 5 Conclusion

This contribution introduces to the current status of the offshore-wind energy in Germany and indicates the problems which exist within the offshore supply chain. The main cause for extensive project delays are bad weather conditions. Accordingly, a concept of a planning system for the coordination of onshore and offshore activities is depicted. The core of this planning system
is a MILP which calculates optimal installation schedules by observing different weather conditions and vessel loading sets. Based on this model, seasonal and up-to-date weather forecasts can be considered and statistical significant results can be gathered. The next working steps include the development of a simulation model, which contains the material flow of offshore and onshore processes. Also, the planning and control of the onshore material supply should be improved by using autonomous control methods.

References:


