A MILP for installation scheduling of offshore wind farms

Bernd Scholz-Reiter, Jens Heger, Michael Lütjen, Anne Schweizer

Abstract— Construction and utilization of offshore wind farms is going to 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 up to 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.

Keywords— Installation Scheduling, Maritime Logistics, Mixed Integer Linear Programming (MILP), Offshore Wind Farm.

I. 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. Optimal configurations for a prospective renewable-based electricity supply sector are still under investigation [1].

In Germany the first offshore wind farm "Alpha Ventus" [2] was opened in April 2010, after the installation of more than 20.000 wind turbines onshore in Germany until the end of the year 2009. Other European countries such as England, Denmark or Sweden, have gained more experiences with the installation of wind farms, which are documented in reports published in [3], [4] and [5]. Beside enormous technical challenges with the components of offshore wind turbines, the support of the underlying logistic processes 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 [6] is planned in Europe, what corresponds to an annual installation of more than 1,000 offshore-wind turbines. The current status and the development of wind energy in the European Union is described in [7]. 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 the 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 are 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. Finally, we conclude and provide an outlook to our next activities.

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II. 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 weather. 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 [8]. 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 onboard of the vessel, as well as personnel capacities, which are needed for the installation processes. In addition, vessel and handling capacities are bounded by the harbor.

A. Installation scenarios and vessel requirements

The installation scheduling of offshore wind farms strongly depends on the current weather conditions on sea. Accordingly, different attempts exists which offer options for an optimized scheduling. It can be distinguished between three installation scenarios [6]. As shown in figure 1, the first option (a) includes the preassembly in a closer situated harbor. Because of a shorter transport time to the wind farm, quick response to weather changes are possible.

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.

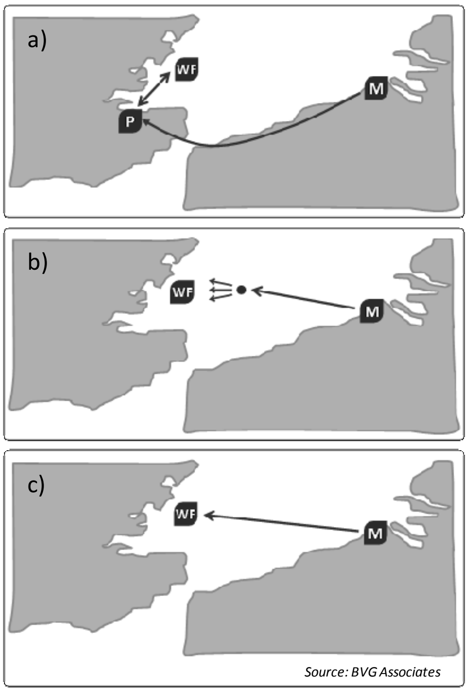

Figure 1: Installation scenarios: a) The components, produced by a manufacturer (M) are transported to the assembly port (P) and assembled there. They are brought to the construction at the wind farm (WF) afterwards, b) the components are transported from manufacturer (M) near to the wind farm (WF). 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).

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.

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 fall 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 MILP, which allows an installation scheduling 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.

Figure 2: Offshore installation vessel with jack-ups (Beluga-Hochtief).

B. 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 during good weather periods, massive material requirements are needed in a short time that must be supported by the whole 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 [9].

Especially for the growing number of OWT-installations in the next ten years, it will be necessary to get well functioning supply chains, which allow a line production of wind farms. The high process transparency, which is e.g. known from the automobile industry [9], will be also important for the offshore assembly. Process disturbances in transport or manufacturing lead to high subsequent costs, because the installation vessel and its crew are delayed. 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.

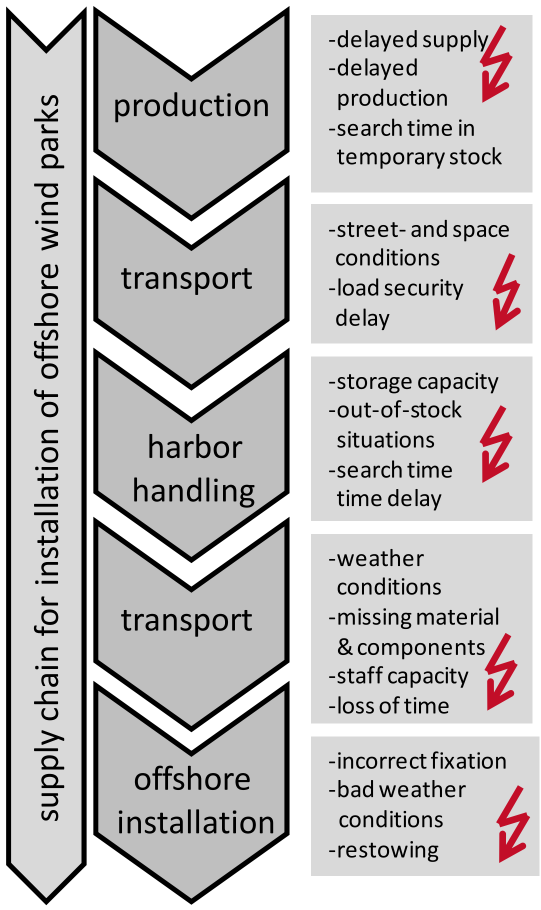

Figure 3: The material flow process and its disturbance variables in the supply chain for the installation of offshore wind farms

The disturbances within the supply chain can reach from capacity problems over quality problems to different traffic and weather conditions. Between production and offshore installation, the supply chain consists of shore-based transport, handling at the harbor and the sea-based transport. For instance, any delay in supply will disrupt the production process of an OWT fundamentally. Due to its high customization a stock of standard material cannot be installed. The produced components cannot be transported like standard logistic objects as they are mostly very bulky and heavy. To take these requirements into account, transports are often performed at night when it is possible to use streets exclusive. Any disturbance of these transports leads to delays of days. Compared to known logistic strategies, these delays are serious. When a ship has to be loaded with site needed components, they have to be located on the terminal in an appropriate time. Out-of-stock situations which can result from a delay in transport have to be avoided. The transport of components by ship to offshore sites depends on weather conditions which have an impact on loading scenarios and the installation in total. Logistic strategies for the offshore industry have to take these challenges into account. As a result, we have to deal with delays in the supply chain. In order to increase the transparency and the application of robust planning and control methods we have to use information technologies for tracking and tracing.

C. 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 30 hours (86-87 % probability of correctness) [10]. 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 [11].

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 being the limited and expensive resources.

III. 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 crew 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 (figure 4).

Additionally, in the near future vessels will become the bottleneck in the wind farm installation process [6]. Therefore, it is important to optimize especially this part of the supply chain.

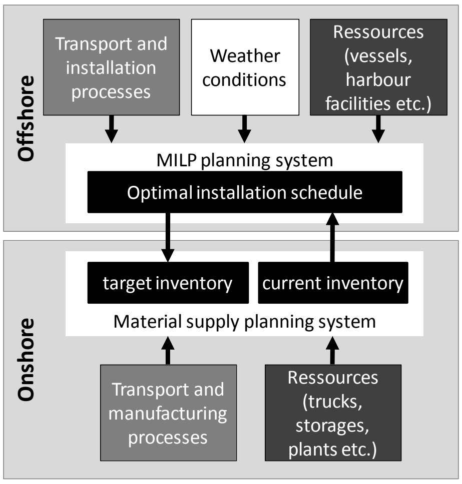

Figure 4: Concept of planning system for coordination of onshore and offshore activities

IV. MILP FOR VESSEL SCHEDULING

As mentioned above we have 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 will probably stay. Their utilization should be as effective 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.

A. Properties of the mathematical model

The following properties of the installation processes are considered by the 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. Three types of weather conditions are modeled
   - good weather: substructures and top-structures can be built.
   - medium weather conditions: only substructures can be built.
   - bad weather conditions: nothing can be built.

The sequence of the installation steps is depicted in figure 5. At first, the vessel loading set is selected. The installation vessel can handle several fixed loading sets, because each set requires its own superstructures on the vessel.

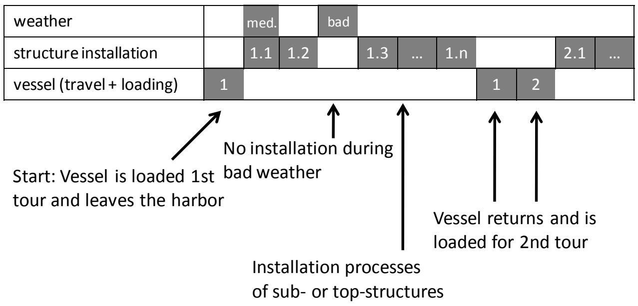

Figure 5: Sequence of installation steps

Several loading sets can be defined, two examples are integrated into model: the first set contains four sub-structures and two top-structures and the second set contains two sub-structures and four top-structures. Basically, the loading set can be extended easily. After the loaded vessel has 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. [12]) with the typical continuous-time representation of a job-shop (e.g. [13]). 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_t: storage; p_t: production; d_t: demand; t: period):

$$s_t = s_{t-1} + p_{t-1} - d_{t-1} \tag{1}$$

The job-shop formulation is more flexible with, e.g. the 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):

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

These two concepts are combined in our model. Scheduling should not be limited to discrete time periods; since we are using the job-shop formulation for the installation process order. To make sure, that for each process the necessary resources are available, the multi-period formulation is used. With this we can ensure that there is always a free sub-structure, if a top-structure should be built and that there are enough structures on the vessel left, to be built.

B. Mixed Linear Integer Program in detail

The following model parameters are used in the MILP. They represent the general conditions and they are defined before the optimization run.

Parameters

tr	Travelling time from harbor to wind farm
tl	Travelling time + loading time at the harbor
vn	Maximum number of vessel tours
mp	Maximum number of processes at each vessel tour
bj	Building time for a sub-structure
bt	Building time for a top-structure
v1j	Number of sub-structures in loading set 1
v2j	Number of sub-structures in loading set 2
v1t	Number of top-structures in loading set 1
v2t	Number of top-structures in loading set 2
tn	Total number of turbines to be built
wp	Number of weather periods
$lw1_p$	Length of period *p* of weather condition 1
$lw2_p$	Length of period *p* of weather condition 2
M	A big number

The following variables are set by the MILP and represent the solution of the optimization run.

Variables

$sb_{v,p}$	Start time of vessel tour *v* and building process number *p*
vs_v	Start time of vessel tour *v*
vr_v	Time of return of vessel tour *v*
$tj_{v,p}$	1 if sub-structure is built at vessel tour *v* and building process *p*, 0 otherwise, *binary variable*
$tt_{v,p}$	1 if top-structure is built at vessel tour *v* and building process *p*, 0 otherwise, *binary variable*
$fj_{v,p}$	Number of available sub-structures (to built top-structures on) at vessel tour *v* and building process *p*
$v1_v$	1 if vessel loading 1 is selected on tour *v*, 0 otherwise, *binary variable*
$v2_v$	1 if vessel loading 1 is selected on tour *v*, 0 otherwise, *binary variable*
$bOAW1_{v,p,t}$	1 if vessel tour *v* and building process *p* is performed before weather condition 1 at period *t*, 0 if performed after, *binary variable*
$bOAW2_{v,p,t}$	1 if vessel tour *v* and building process *p* is performed before weather condition *t*, 0 if performed after, *binary variable*
st	Sum of building start times

The goal of the optimization is to minimize the time needed to build the wind farm, i.e. the return time of the last vessel.

Minimize vr_{mv} + st; (3)

subject to

The vessel can leave the harbor, when it has arrived from the previous tour.

$$vs_{i+1} \geq vr_i + tr; \quad i = 1, 2...mv \tag{4}$$

The first building process can start after the vessel has arrived at the wind farm.

$$sb_{i,1} \geq vs_i + tl; \quad i = 1, 2...vn \tag{5}$$

For every vessel tour and for each sequence of building processes at this tour, the start time plus the building time of either the sub-structure or the top-structure must be finished before the next process can start.

$$sb_{i,j} + bj\ tj_{i,j} + bt\ tt_{i,j} \leq sb_{i,j+1}; \quad i = 1, 2...vn, j = 1, 2...mp \tag{6}$$

The earliest time the vessel can return to the harbor begins, when all building processes are performed.

$$vr_i \geq sb_{i,mp} + bj\ tj_{i,mp} + bt\ tt_{i,mp}; \quad i = 1, 2...vn \tag{7}$$

One loading setting must be selected.

$$v1_i + v2_i \leq 1; \quad i = 1, 2...vn \tag{8}$$

For each vessel tour the number of sub-structures, which can be built is limited by the maximum number of available sub-structures defined by the loading selection.

$$\sum_{j=1}^{mp} tj_{i,j} \leq v1_i\ v1j + v2_i\ v2j; \quad i = 1, 2...vn \tag{9}$$

For each vessel tour the number of top-structures, which can be built is limited by the maximum number of available top-structures defined by the loading selection.

$$\sum_{i=1}^{mp} tt_{i,j} \leq v1_i\ v1t + v2_i\ v2t; \quad i = 1, 2...vn \tag{10}$$

The total number of built sub-structures must fit the number of total turbines.

$$\sum_{i=1}^{vn} \sum_{j=1}^{mp} tj_{i,j} = tn;$$

The total number of built sub-structures must fit the number of total turbines.

$$\sum_{i=1}^{vn}\sum_{j=1}^{mp} tt_{i,j} = tn; \qquad (11)$$

At each process building step either a sub-structure or a top-structure can be built.

$$tj_{i,j} + tt_{i,j} \leq 1; \quad i = 1,2...vn, j = 1,2...mp \qquad (12)$$

The number of available sub-structures equals the number of available sub-structures from the period before plus either the newly built sub-structure or minus the newly build top-structure. This is according to the schema depict in (1).

$$fj_{i,j+1} = fj_{i,j} + tj_{i,j} - tt_{i,j}; \quad i = 1,2...vn, j = 1,2...pm \qquad (13)$$

This is also true, when a new vessel tour begins.

$$fj_{i+1,1} = fj_{i,mp} + tj_{i,mp} - tt_{i,mp}; i = 1,2...vn \qquad (14)$$

The available number of sub-structures at the beginning is obviously 0.

$$fj_{1,1} = 0 \qquad (15)$$

The number of available sub-structures has to be positive, otherwise a top-structure could be built without a base, which is naturally not possible.

$$fj_{i,j} \geq 0; \quad i = 1,2...vn, j = 1,2...mp \qquad (16)$$

The following two equations (17) and (18) make sure that no building process overlaps with weather conditions 1. Either the start time plus the building duration is smaller than the start time of the weather condition or the weather condition is already over.

$$sb_{i,j} + bj\ tj_{i,j} + bt\ tt_{i,j} \leq w1_t + boaw1_{i,j,t} M; \quad i = 1,2...vn, j = 1,2...p, t = 1,2...wp \qquad (17)$$

$$sb_{i,j} \geq w1_t + lw1_t - (1 - boaw1_{i,j,t})\ M; \quad i = 1,2...vn, j = 1,2...p, t = 1,2...wp \qquad (18)$$

The following two equations (19) and (20) ensure, that during weather condition 2 no building of top-structures occurs. Building of sub-structures is possible, see term "-$tj_{i,j}$ M". This is the case, because during mild wind, sub-structures (jackets) can be built, but for top-structures installations the wind is too strong.

$$sb_{i,j} - tj_{i,j}\ M + bt\ tt_{i,j} \leq w2_t + boaw2_{i,j,t}\ M; \quad i = 1,2...vn, j = 1,2...p, t = 1,2...wp \qquad (19)$$

$$sb_{i,j} \geq w2_t + lw2_t - (1 - boaw2_{i,j,t})\ M; \quad i = 1,2...vn, j = 1,2...p, t = 1,2...wp \qquad (20)$$

Equation (21) is added, to ensure, that building processes start as soon as possible. Sometimes there are time windows in which a process should be performed, without changing the total finishing time. But since weather forecast could be wrong the earliest possible starting time is taken.

$$st \geq \sum_{i=1}^{vn}\sum_{j=1}^{mp} sb_{i,j}; \quad i = 1,2...vn, j = 1,2...p \qquad (21)$$

We have decided to define the number of vessel tours (vn) manually, because this significantly speeds up the solving time due to less complexity as short tests have shown. With a short capacity analyses the number can be calculated easily and a few additional runs with one or two more tours can be calculated quickly and compared afterwards.

C. Complexity and Solver runtime

The planning problem belongs to the NP-hard problems (job-shop scheduling), but since the planning model considers only one vessel, realistic scenarios can be calculated in acceptable time. SCIP [**Fehler! Verweisquelle konnte nicht gefunden werden.**4] was able to calculate an optimal solution for the example provided in the next chapter 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 [15] could increase these numbers again.

D. 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 components of the wind turbines are ready to be loaded on 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.

Input parameters	
Number of wind turbine installations	12
Vessel loading time	8
Vessel travel time to/from wind farm	4
Sub-structure installation time	24
Top-structure installation time	48
Medium weather start times	Array of weather start times
Medium weather durations	Array of weather condition durations
Bad weather start times	Array of weather start times
Bad weather durations	Array of weather condition durations

Table 1: Parameters for used in the example

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.

E. 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 simulation runs are performed, significant statistical results can be gathered.

F. Further work and outlook

In further work the MILP can be extended to a stochastic model, which can consider uncertain weather conditions directly. Stochastic programming is used, e.g. for planning in telecommunication networks and financial investments as well as in the supply chain management [16]. This method can be useful for our approach as well. Instead of manually simulating different weather conditions by solving the model with different weather data, probabilistic data for the weather conditions can be considered, i.e. for the uncertain data likelihood distributions are accepted as inputs for the linear optimization model. Thus expectations of the objective function can be optimized [17].

Another interesting extension to further increase the utilization of the vessel and its crew, especially when unexpected weather changes occur, could be to include maintenance processes into the scheduling [18] [19].

V. CONCLUSION

This contribution introduces to the current state of the offshore-wind energy in Germany and indicates the problems which exist within an offshore supply chain. The main cause for extensive project delays is 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 regarding 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.

After calculating an optimal installation schedule, suitable target inventories can be calculated for the whole supply chain by using delivery times. Occurring material shortages will be considered by rolling horizon planning. Depending on the actual inventories new installation will be calculated. The next working steps include the development of a simulation model, which contains the material flow of offshore and onshore processes.

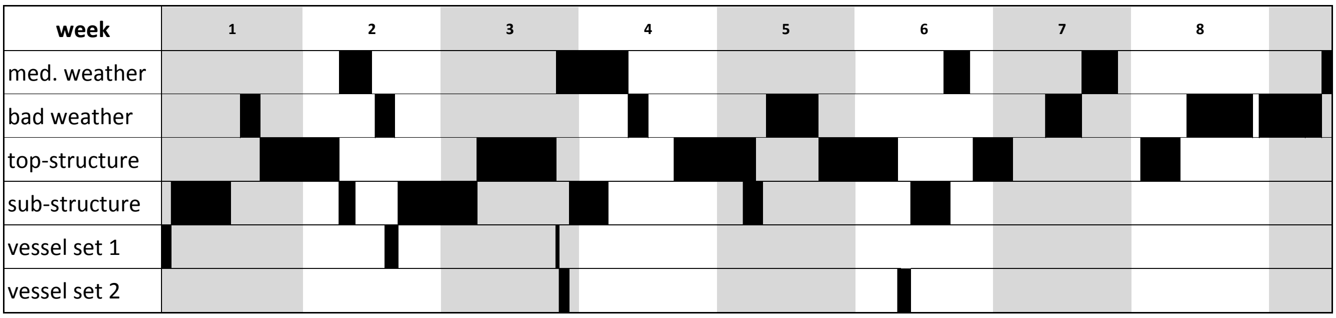

Figure 6: Example Gantt chart of a wind farm building schedule

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