A benders decomposition approach for solving the offshore wind farm installation planning at the North Sea - *Evrim Ursavas*

Wind turbines constitute one of the alternatives towards a sustainable electricity production. In particular, offshore wind turbines (OWT) present higher performances than onshore wind turbines. However, OWT requires higher investments, with rental costs and manpower costs representing the largest part of the costs. For example, the installation vessel used is a Jack-up platform with a very high daily rental cost (140000€). These costs are themselves dependent on the duration of the installation of the OWT. According to Wagenborg and MPI Offshore, two Dutch offshore operators, weather conditions are the main cause of uncertainties leading to significant delays and hence higher costs. This paper provides a model and a solving method for the installation planning of offshore wind farms under meteorological uncertainties.

The installation of a wind farm can be decomposed into three main steps. The first step consists in the pre-assembly of some specific elements onshore. The second step consists in the building of the foundations under the sea. The third step is itself decomposed into two sub-steps: the assembly of sub-structures and the assembly of top-structures. The third step is the most sensitive to meteorological hazards and hence, is the main topic of the paper. The operations of the installation vessel are divided into successive tours. Each tour starts by the loading of the vessel at the harbor and the trip towards the construction site. The tour is then decomposed into a certain number of processes. Each process consists in the assembly of either a sub-structure or a top-structure. The tour ends with the return trip of the vessel to the harbor, then the next tour can start. Weather conditions have an impact on the processes by slowing down or cancelling some tasks, which constitute the main cause of delays. The weather impact depends on the difference between the real weather and the forecasts, in particular regarding to the start date of the meteorological event and its duration. To address these uncertainties, a two-stage stochastic integer program is proposed. The first stage consists in selecting the rent duration of the installation vessels, while the second stage consist in selecting the date of the various processes. The proposed solution uses a Benders decomposition.

In the model, the time is discretized into weather period. For each weather period, the weather is discretized into three classes: good, medium or bad. During good weather, both sub and top-structures can be built. Only sub-structure can be built during medium weather while neither sub or top-structures can be built during bad weather. Then, scenarios are built by considering sequences of weather classes over several periods. For each scenario ω, a probability of occurrence $p(\omega)$ is defined.

The decision variables are described as the following. In the first stage, the starting time and returning time of a tour are chosen before the actual weather can be known. In the second stage, the loading set (number of sub-structures and top-structures loaded aboard the vessel), the starting time of each process, and the type of structure to be built on each process (sub or top) are chosen according to actual weather constraints. To describe the constraints, a multi-period production formulation is used (to ensure that a sub-structure is available each time a top-structure is built) as well as a job-shop formulation (to ensure that a task cannot start before the previous task has not ended). The objective function is to minimize the total return time of all the vessel tours summed with the expectation of the total building time of all the processes of all the tours.

Hence, the stochastic program can be expressed with a deterministic equivalent. However, the number of scenarios makes it impossible to be solved in its extensive form due to computational issues. This is why the Benders decomposition will be used. The variables kept in the Benders master problem are the starting time of the tours and the returning time of the tours. All the other variables (loading set, starting time and type of structure for each process) are decided in the sub-problem. Hence, the uncertainties only affect the sub-problem. At each iteration of the Benders decomposition process, the master problem is solved providing a lower bound. Then, the sub-problem is solved for each scenario ω. The expectation over the scenarios $\omega \in \Omega$ provides an upper bound (using the solutions of the master problem for the variables of the master problem). If the difference between the lower and upper bounds is greater than a given tolerance, an optimality cut is added to the master problem and a new iteration can start (or a feasibility cut is added to the master problem if the sub-problem is unbounded). Since some variables are binary, the Benders decomposition is used to solve a linear relaxation of the problem inside a Branch and Bound framework used to obtain integer solutions. For branching, priority is given to variables corresponding to scenarios with the highest probability, as well as to variables corresponding to the earlier time periods of the project.

This solution is applied to two real wind farm projects in the North Sea. Real weather data are used to build the scenarios: wind limits are identified by experts to define the three weather classes, then the time is discretized according to the dates and durations of the weather events. In the first place, the model is tested on small-scale wind farms (16 turbines to be installed), succeeding to provide flexible solutions regarding weather constraints. In particular, allowing to build sub and top structures simultaneously seems to reduce the delays. This test also points the necessity to use a Benders decomposition approach since the extensive form generates a tree which was too large to fit into the memory. Then, the model is tested with two real projects: “Bard 1” (80 turbines) and “Borkum West” (40 turbines) using the CPLEX solver. The computational time increases with the number of rows and columns, themselves proportional to the number of scenarios. The wind limits of “Borkum West” are lower than for “Bard 1”: the model shows that this increased the installation duration by two months. For this two real projects, the model seems to provide good approximation of the real installation duration (which were far longer than the planned duration). Finally, some tests have been conducted to evaluate the effects of the distance of the wind farm to the shore and the vessel load. Results shows that the more the wind farm is far from the shore, the more it is valuable (regarding the delays) to increase the vessel load.

Some remarks

- Constraints (14) and (37) seems to be erroneous: j should be replaced by P.
- Constraints (15) to (18) seems to indicate that the right definition of $wbb_{i,j,t}(\omega)$ is: 1 if vessel tour i building process j is performed *after* (not before) bad weather condition stb_t. Same for $wbm_{i,j,t}(\omega)$.
- In constraints (18) and (43), the term $-bs_{i,j}(\omega) \cdot M$ might be lacking in the left member to allow the building process of a sub-structure during a medium weather condition.