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Strategic Optimization of Offshore Wind Farm Installation

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Abstract. This work describes logistical planning of offshore wind farm (OWF) installation through linear programming. A mixed integer linear programming (MILP) model is developed to analyze cost-effective port and vessel strategies for offshore installation operations. The model seeks to minimize total costs through strategic decisions, that is decisions on port and vessel fleet and mix. Different vessels, ports and weather restrictions over a fixed time horizon are considered in the model. Several deterministic test cases with historic weather data are implemented in AMPL, and run with the CPLEX solver. The results provide valuable insight into economic impact of strategic decisions. Numerical experiments on instances indicate that decision aid could be more reliable if large OWFs are considered in fractionated parts, alternatively by developing heuristics.

Keywords: offshore wind installation, mixed integer linear programming, fleet optimization

1 Introduction

Renewable energy is a growing industry within the energy sector. The growth is motivated by issues like the challenge of global climate change, the increasing need for energy, and new market opportunities. Harvesting energy from the wind is becoming a developed renewable energy technology. Operating offshore involves greater challenges than onshore, and electricity production from offshore wind farms (OWFs) is today considered expensive.

Offshore construction of a wind farm requires a lot of logistical planning. Vessels and/or barges must transport and install large components in a demanding environment. The challenges include restrictive weather conditions contributing to delays on very costly operations. Farm sites and turbine components are expected to keep growing in size, and wind farm locations are expected to be placed further away from shore. In addition, an increasing number of specialized installation vessels are becoming available on the market. Crucial decisions in planning the installation process include choosing the most cost-effective vessels, figuring out how components should be loaded and installed, and choosing which port to operate from to minimize expenses and delays.

Operational research models for OWFs are focused on operation and maintenance (O&M) of fully commissioned farms. Some work is also done to support vessel scheduling of OWF installation [6, 7]. To the authors' knowledge, limited published research is focusing on the installation fleet size and mix problem through linear programming. This work seeks to aid decisions for installation fleet size and mix, by means of a mixed integer linear programming (MILP) model.

Section 2 describes the framework of the model in detail, and its mathematical formulation is given in Section 3. Section 4 presents realistic numerical experiments run with the model, and the paper is concluded in Section 5.

2 Problem Description

The model, to be detailed in the next section, considers the offshore installation stage of a given number of wind turbines.

Each turbine consists of components that can mainly be split into three categories: sub-structures, cables and top-structures. In addition, OWFs consist of one or more sub-stations collecting all the energy generated by the turbines. The options are few on how to perform installation of sub-structures, cables and sub-stations, thus the problem considered concerns installations of top-structures. These structures mainly consist of tower, nacelle, hub and blades. Top-structures for a complete turbine can be partly assembled onshore, and will usually be installed by the same vessel.

All components must be loaded and transported by some vessel to the OWF. Next, the transported components are installed at turbine locations. Before each installation, vessels commonly lower pillars into the seabed (jack-up) to raise their deck above the sea, creating stable platforms where lifting operations can be performed safely given satisfactory weather conditions. After installation is complete, the vessel performs jack-down, and transits to the next turbine or back to port. Depending on the possible onshore assembly of certain components, a number of loading and installation lifts will take place for each turbine.

Vessels can differ in effectiveness and costs, and usually perform several cycles of loading, transportation and installation. The same vessel may load different numbers of turbines on different cycles. Any vessel transit, jack-up/jack-down and installation is restricted by weather conditions.

Chartering vessels is expensive, and there are thus high costs of weather delays. The main decisions we want to support are which vessels and ports to use, how many cycles each vessel performs and how many turbines each vessel loads on each cycle. These decisions will depend on vessel and port costs, transit distances, vessel specifications and weather realizations causing potential delays.

Upon planning installation of an OWF, the goal is to perform the complete installation with the least amount of costs.

3 Model Formulation

The current section presents the mathematical formulation of the MILP model dealing with the problem presented in Section 2.

Section 3.1 introduces the model framework in terms of input data, and Section 3.2 presents variables representing decisions supported by the model. The objective function is defined in Section 3.3, and Section 3.4 introduces constraints ensuring operation assignment and time tracking. Finally, weather windows are introduced in Section 3.5.

3.1 Model Framework

The model supports decisions on which vessel(s) to use, and which port vessel(s) are to operate from. Vessels are contained in the set V, and ports are contained in the set K.

Offshore operations can be categorized into four tasks: jack-up, installation, jack-down and turbine transit, and they will henceforth be referred to as O_1, O_2, O_3 and O_4, respectively.

Input data in the model represent the following operation durations, which are dependent on vessel and port:

t_v^L: Time needed to load one turbine on vessel $v \in V$,

t_{kv}^K: Time needed for vessel $v \in V$ to transit between port $k \in K$ and farm,

t_v^i: Time to perform operation O_i with vessel $v \in V$, $i = 1, ..., 4$.

The model considers each turbine to be completely installed by exactly one vessel, which means the model does not have to consider each component explicitly. Vessels also represent a defined way of assembling components of one complete turbine, e.g. assemble nacelle, hub and two blades together in one piece. Time consumption for loading and installation is mainly dependent on the number of lifts needed. The assembly of components is therefore reflected through the input data identifying loading time (t_v^L) and installation time (t_v^2). All components are assumed available at potential ports, so the model does not consider possible inventory delays. There are no restrictions on the number of vessels loading at the same port simultaneously.

The transit durations (t_{kv}^K, t_v^4) are not dependent on turbine locations. This is because the model considers transit time to a turbine from port $k \in K$, and transit time from a turbine to its neighbouring turbine, to be equal for all turbines for vessel $v \in V$. Simplifications on the transit times can be defended with arguments that the distance from port to farm is significantly greater than the distance across the farm, and that the turbines installed on one cycle is likely to be neighbouring.

Vessel $v \in V$ is limited to carry Y_v turbines per cycle, and limited to perform at most U_v cycles.

The entire OWF must be installed within a given time horizon. The model considers *continuous time*. This means that the length of the time horizon is given as a parameter, which we denote P. The total number of turbines in the OWF is denoted R.

3.2 Decision Variables

Because time is modelled continuously, all variables representing the time at which operations take place are defined separately from the variables concerning operation assignment. The dimensions of the variable vectors are therefore smaller than what is likely to be the case in a discrete-time model.

The following assignment variables are binary:

$$\delta_k = \begin{cases} 1, & \text{if port } k \in K \text{ is in use,} \\ 0, & \text{otherwise,} \end{cases}$$

$$\gamma_v = \begin{cases} 1, & \text{if vessel } v \in V \text{ is used,} \\ 0, & \text{otherwise,} \end{cases}$$

$$x_{kvu} = \begin{cases} 1, & \text{if vessel } v \in V \text{ operates from port } k \in K \\ & \text{on cycle } u = 1, ..., U_v, \\ 0, & \text{otherwise,} \end{cases}$$

$$\theta_{vuy} = \begin{cases} 1, & \text{if vessel } v \in V \text{ installs } y = 1, ..., Y_v \text{ or more turbines} \\ & \text{on cycle } u = 1, ..., U_v, \\ 0, & \text{otherwise.} \end{cases}$$

The variables θ_{vuy} and x_{kvu} are represented in terms of special ordered sets of type 2 (SOS2) [3]. This means that if vessel $v \in V$ installs $y' \leq Y_v$ turbines on cycle $u' = 1, ..., U_v$, that is if $\theta_{vu'y'} = 1$, we have that $\theta_{vu'y} = 1$ for all $y = 1, ..., y'$, and for some $k \in K$, we have that $x_{kvu} = 1$ for all $u = 1, ..., u'$.

Continuous variables are defined to keep track of time:

$q_{vu} \in \mathbb{R}_+$: Time when vessel $v \in V$ starts cycle $u = 1, ..., U_v$,

$e_{vu} \in \mathbb{R}_+$: Time when vessel $v \in V$ ends cycle $u = 0, ..., U_v$,

$s^i_{vuy} \in \mathbb{R}_+$: Time when vessel $v \in V$ starts operation O_i at the yth turbine on cycle $u = 1, ..., U_v$, $y = 1, ..., Y_v$, $i = 1, ..., 4$,

$E_v \in \mathbb{R}_+$: Total time vessel $v \in V$ is chartered.

Note that the variables e_{vu} are defined for $u = 0$, where e_{v0} represents the charter start of vessel $v \in V$.

The variables s^4_{vuy} are defined as the time when vessel $v \in V$ *leaves* turbine y on the uth cycle, which may be a transit to a turbine (if $y < Y_v$ and $\theta_{vu,y+1} = 1$) or to port (if $y = Y_v$ or $\theta_{vu,y+1} = 0$).

3.3 Costs and Objective Function

The following costs relate to ports and vessels:

c_k^K: Cost incurred if port $k \in K$ is used,
c_v^{TC}: Time charter cost per time unit for vessel $v \in V$,
c_v^M: Mobilization cost for starting chartering of vessel $v \in V$.

The goal of the model is to minimize the costs introduced above. Consequently, the objective function is defined in the following way:

$$\min \sum_{k \in K} c_k^K \delta_k + \sum_{v \in V} \Big(c_v^M \gamma_v + c_v^{TC} E_v \Big). \tag{1}$$

The first sum in (1) measures total port operation costs, while the last sum measures total costs of chartering and mobilizing vessels.

It can be argued that there are more costs related to OWF installation, e.g. fuel and crew costs. However, the charter cost of a jack-up vessel may include several operational costs depending on the contract [4]. The total jack-up vessel charter cost can also be identified as the dominant cost related to jack-up vessels for OWF O&M activities [5]. The terms in (1) are therefore assumed to be sufficient in the context of optimization, where the aim is to support strategic decisions.

3.4 Constraints

The following constraints ensure that all installation operations are assigned to a vessel and a cycle. Further, they make the assignment variables introduced in Section 3.2 consistent with each other:

$$\sum_{v \in V} \sum_{u=1}^{U_v} \sum_{y=1}^{Y_v} \theta_{vuy} = R, \tag{2}$$

$$\theta_{vuy} \le \gamma_v, \quad v \in V,\ u = 1, ..., U_v,\ y = 1, ..., Y_v, \tag{3}$$

$$x_{kvu} \le \delta_k, \quad k \in K,\ v \in V,\ u = 1, ..., U_v, \tag{4}$$

$$\sum_{k \in K} x_{kvu} \le 1, \quad v \in V, u = 1, ..., U_v, \tag{5}$$

$$x_{kvu} \le x_{kv,u-1}, \quad k \in K,\ v \in V,\ u = 2, ..., U_v, \tag{6}$$

$$\theta_{vu1} \le \sum_{k \in K} x_{kvu}, \quad v \in V,\ u = 1, ..., U_v, \tag{7}$$

$$\theta_{vuy} \le \theta_{vu,y-1}, \quad v \in V,\ u = 1, ..., U_v,\ y = 2, ..., Y_v, \tag{8}$$

$$\theta_{vuy} \le \theta_{v,u-1,1}, \quad v \in V,\ u = 2, ..., U_v,\ y = 1, ..., Y_v. \tag{9}$$

Constraint (2) ensures all turbines are installed by some vessel $v \in V$ on some cycle u.

Constraints (3) make sure that vessels are assigned operations only if they are mobilized, and constraints (4) ensure ports are open if a vessel cycle is initiated there.

Ensuring that each vessel operates from at most one port, constraints (5) and (6) state, respectively, that a vessel cycle can start from at most one port, and that the succeeding cycle, if any, starts from the same port. Constraints (7) say that if vessel $v \in V$ installs at least one turbine on its uth cycle, then it also leaves some port.

Consistently with the SOS2-representation of θ_{vuy}, constraints (8) say that vessel $v \in V$ installs at least $y-1$ turbines if it installs y turbines or more on a cycle. Likewise, constraints (9) state that if vessel v installs y turbines on its uth cycle, it also installs at least one turbine on cycle $u-1$.

The next constraints ensure correct time tracking:

$$e_{v,u-1} + t_v^L \sum_{y=1}^{Y_v} \theta_{vuy} \leq q_{vu}, \quad v \in V,\ u = 1, ..., U_v, \tag{10}$$

$$q_{vu} + \sum_{k \in K} t_{kv}^K x_{kvu} \leq s_{vu1}^1, \quad v \in V,\ u = 1, ..., U_v, \tag{11}$$

$$s_{vuy}^{i-1} + t_v^{i-1} \theta_{vuy} \leq s_{vuy}^i, \quad v \in V,\ u = 1, ..., U_v,\ y = 1, ..., Y_v,\ i = 2, ..., 4, \tag{12}$$

$$s_{vu,y-1}^4 + t_v^4 \theta_{vuy} \leq s_{vuy}^1, \quad v \in V,\ u = 1, ..., U_v,\ y = 2, ..., Y_v, \tag{13}$$

$$s_{vuY_v}^4 + \sum_{k \in K} t_{kv}^K x_{kvu} \leq e_{vu}, \quad v \in V,\ u = 1, ..., U_v, \tag{14}$$

$$e_{vu} \leq P, \quad v \in V,\ u = 0, ..., U_v, \tag{15}$$

$$e_{vu} - e_{v0} \leq E_v, \quad v \in V,\ u = 1, ..., U_v. \tag{16}$$

Recall that e_{vu} is defined for all $v \in V$ and $u = 0, ..., U_v$, where e_{v0} represents the charter start of vessel v.

Constraints (10) ensure that vessel $v \in V$ finishes loading before leaving port and starting its uth cycle, and constraints (11) make sure vessel v arrives at the first turbine after the transit from port is complete.

Constraints (12) ensure that vessel $v \in V$ performs operation O_{i-1} before the successive operation O_i at the yth turbine. To connect the time tracking between turbines, constraints (13) make sure vessel v arrives at the yth turbine after the transit from the preceding turbine is complete. All operations are repeated until all loaded turbines are installed on a cycle.

Constraints (14) make sure vessel $v \in V$ returns to port before ending its uth cycle. Constraints (15) ensure all cycles end within the time horizon, and constraints (16) ensure the continuous time variable E_v is no less than the total charter length of vessel v.

3.5 Weather Windows

The model deals with weather restrictions through time intervals, referred to as *weather windows*, in which certain operations are feasible.

The model considers transit, jack-up, jack-down and installation to be weather restricted, and these operations must be performed within some weather window. The following input data are defined:

W_v^i: Number of weather windows for operation O_i with vessel $v \in V$, $i = 1, ..., 4$,

a_{vn}^i: Start of weather window $n = 1, ..., W_v^i$ for operation O_i with vessel $v \in V$, $i = 1, ..., 4$,

b_{vn}^i: End of weather window $n = 1, ..., W_v^i$ for operation O_i with vessel $v \in V$, $i = 1, ..., 4$.

Note that the weather windows are only dependent on vessel and operation. Recall from Section 3.1 that vessels also represent a way of assembling components.

Binary decision variables are introduced to identify in which weather window which operation is performed:

$$N_{vuyn}^i = \begin{cases} 1, & \text{if vessel } v \in V \text{ performs operation } O_i \text{ at the } y\text{th turbine} \\ & \text{on cycle } u \text{ in weather window } n = 1, ..., W_v^i,\ u = 1, ..., U_v, \\ & y = 1, ..., Y_v,\ i = 1, ..., 3, \\ 0, & \text{otherwise,} \end{cases}$$

$$N_{vuyn}^4 = \begin{cases} 1, & \text{if vessel } v \in V \text{ transits to the } yth \text{ turbine on cycle } u \\ & \text{in weather window } n = 1, ..., W_v^4,\ u = 1, ..., U_v, \\ & y = 1, .., Y_v + 1, \\ 0, & \text{otherwise.} \end{cases}$$

Note that the binary variables N_{vuyn}^4 represent the weather windows in which transit *to* the yth turbine for $y = 1, ..., Y_v + 1$ is performed. Thus, the transit to the first turbine to be installed on a cycle is a transit from port to farm. Analogously, the transit to the $(Y_v + 1)$th turbine represents a transit to port.

The binary decision variables above are dependent on the assignment variables introduced in Section 3.2:

$$\sum_{n=1}^{W_v^4} N_{vuyn}^4 = \theta_{vuy}, \quad v \in V,\ u = 1, ..., U_v,\ y = 1, ..., Y_v, \tag{17}$$

$$\sum_{n=1}^{W_v^i} N_{vuyn}^i = \theta_{vuy}, \quad v \in V,\ u = 1, ..., U_v,\ y = 1, ..., Y_v,\ i = 1, ..., 3, \tag{18}$$

$$\sum_{n=1}^{W_v^4} N_{vu,Y_v+1,n}^4 = \theta_{vu1}, \quad v \in V,\ u = 1, ..., U_v. \tag{19}$$

Constraints (17)-(19) make sure assigned operations must happen within exactly one weather window. In particular, constraints (19) state that if vessel $v \in V$ installs at least one turbine on cycle u, then it transits back to port in exactly one weather window.

Transits can be from port to farm, in between turbines or from farm to port, and all transits are subject to the same weather restrictions:

$$\sum_{n=1}^{W_v^4} N_{vu1n}^4 a_{vn}^4 \leq q_{vu}, \ v \in V, \ u = 1, ..., U_v, \tag{20}$$

$$q_{vu} + \sum_{k \in K} t_{kv}^K x_{kvu} - P(1 - \theta_{vu1}) \leq \sum_{n=1}^{W_v^4} N_{vu1n}^4 b_{vn}^4, \ v \in V, \ u = 1, ..., U_v, \tag{21}$$

$$\sum_{n=1}^{W_v^4} N_{vu,y+1,n}^4 a_{vn}^4 \leq s_{vuy}^4, \ v \in V, \ u = 1, ..., U_v, \quad y = 1, ..., Y_v, \tag{22}$$

$$s_{vu,y-1}^4 + t_v^4 - P(1 - \theta_{vuy}) \leq \sum_{n=1}^{W_v^4} N_{vuyn}^4 b_{vn}^4, \ v \in V, \ u = 1, ..., U_v, \quad y = 2, ..., Y_v, \tag{23}$$

$$s_{vuY_v}^4 + \sum_{k \in K} t_{kv}^K x_{kvu} - P(1 - \theta_{vu1}) \leq \sum_{n=1}^{W_v^4} N_{vu,Y_v+1,n}^4 b_{vn}^4, \ v \in V, \ u = 1, ..., U_v. \tag{24}$$

Constraints (20)-(21) make sure all transits from port to farm are scheduled within the chosen weather window, and constraints (22)-(23) have an analogous function for transits between turbines.

Constraints (24), together with (22) for $y = Y_v$, make sure all transits from farm to port are scheduled within their chosen weather window. Note that constraints (22) for $y = Y_v$ and (24) restrict the transit back to port through the time variable $s_{vuY_v}^4$, because $s_{vuY_v}^4$ equals the time at which vessel $v \in V$ starts its transit back to port on its uth cycle. This is accomplished by constraints (12)-(13).

Constraints concerning operation O_i for $i = 1,..,3$ are defined in a similar way:

$$\sum_{n=1}^{W_v^i} N_{vuyn}^i a_{vn}^i \leq s_{vuy}^i, \quad v \in V,\ u = 1, ..., U_v,$$
$$y = 1, ..., Y_v,\ i = 1, ..., 3 \tag{25}$$

$$s_{vuy}^i + t_v^i - P(1 - \theta_{vuy}) \leq \sum_{n=1}^{W_v^i} N_{vuyn}^i b_{vn}^i, \quad v \in V,\ u = 1, ..., U_v,$$
$$y = 1, ..., Y_v,\ i = 1, ..., 3 \tag{26}$$

Constraints (25)-(26) ensure vessel $v \in V$ executes operation O_i on cycle u within the weather window chosen for the operation.

Note that some constraints, e.g. (26), are only constraining if an operation is assigned to vessel $v \in V$, that is if $\theta_{vuy} = 1$.

4 Numerical Experiments

Several test instances with the model introduced in Section 3 are presented in this section. Instances are inspired by realistic data gathered from relevant literature [1, 8], and the main purpose of these numerical experiments is to test how large instances the model can handle.

The model is implemented in AMPL, and the solver used is CPLEX version 12.5.1. Default values [10] on all the parameters of the solver is used to solve the MILP instances. All experiments where run on a computer with 2 Intel Core2 6600 Duo E6550 processors with a frequency of 2.33 GHz and 3.7 GB memory.

4.1 Test Instances

Cost data for charter rates are mainly inspired by [1], and vessel mobilization cost is assumed to be 5 times the charter cost.

The physical reality behind some vessel $v \in V$, is that transportation and installation operations are performed by two different barges. Involvement of more than one barge in such a collaboration is however irrelevant to the model, and consequently, we refer to their combined use as one vessel contained in V.

Henceforth, each vessel under consideration is of either of the following types:

1. The ”feed” strategy (FS)
2. The ”bunny transit” strategy (BTS)
3. The ”unmounted transit” strategy (UTS)

The ”feed” strategy (FS) represents two barges that need two towing tugs to be mobilized. One barge only transports (feeds) components from port to farm, and the other barge, located in the wind farm, only performs installations. The

FS can carry up to 10 turbines in 5 parts on each cycle. The FS is vulnerable to wave conditions [1].

The "bunny transit" strategy (BTS) consists of one self-propelled installation vessel performing all operations. The BTS can load up to 4 turbines in 3 parts (in a "bunny-ear" configuration [1, 8]) on each cycle. The BTS is sensitive to installation lifts and transits due to wind forces acting on the partly assembled rotor.

The "unmounted transit" strategy (UTS) is identical to the BTS, except that each turbine is loaded and installed in 5 parts. Therefore, the UTS can carry up to 8 turbines on each cycle. Charter rate is assumed lower than the BTS since each lift requires less crane capacity, and wind restrictions are less strict because of the unmounted components.

Specifications of the three vessels are given in Tab. 1. Time is scaled to working days, where one working day is 12 hours. Loading/installation duration is dependent on the number of lifts, i.e., how components are assembled.

Three ports are defined with increasing distance to farm site and decreasing costs in Tab. 2.

Table 1. Input data for the considered strategies.

Strategy	**FS**	**BTS**	**UTS**
Charter rate [$/day]	144,000	200,000	180,000
Mobilization cost [$]	720,000	1,000,000	900,000
Time, load [day]	0.83	0.5	0.83
Time, setup [day]	0.125	0.083	0.083
Time, install [day]	1.00	0.67	1.00
Time, turbine transit [day]	0.011	0.004	0.004
Turbines per cycle [pcs]	10	4	8
Wind restriction, transit [m/s]	20	15	20
Wind restriction, jack-up/down [m/s]	20	15	20
Wind restriction, install [m/s]	10	8	12
Wave restriction, transit [m]	1.5	3.0	3.0
Wave restriction, jack-up/down [m]	1.5	2.0	2.0
Wave restriction, install [m]	5.0	5.0	5.0

Table 2. Input data for the considered ports.

Port	Fixed cost c_k^K [$]	Transit FS [day]	Transit BTS [day]	Transit UTS [day]
Port 1	1,000,000	2.67	1.08	1.08
Port 2	2,000,000	1.58	0.67	0.67
Port 3	3,000,000	0.42	0.25	0.25

The resolution of weather data is one working day, i.e. vessel $v \in V$ either can or cannot perform a given operation during one entire working day. A weather window for an operation is implemented as a closed time interval, in which wind speed and significant wave height are below their respective maximum values (see Tab. 1), during one or more working days. In all the current instances, historical wind and wave data for an offshore site from the year 2000 are supplied by Metno [9] from the NORA10 reanalysis with a 10 km horizontal resolution.

We assume that the weather restrictions that apply to jack-up operations are identical to those applying to jack-down (see Tab. 1). Hence, $W_v^1 = W_v^3$, and also $a_{vn}^1 = a_{vn}^3$ and $b_{vn}^1 = b_{vn}^3$.

We consider three hypothetical OWFs: 20 turbines to be installed in 1 month (OWF 1), 40 turbines to be installed in 3 months (OWF 2), and 100 turbines to be installed in 5 months (OWF 3).

In the first set of experiments, we let V consist of one vessel of each of the types specified in Tab. 1-2 ($|V| = 3$). In the second set, V consists of two vessels of each type ($|V| = 6$).

4.2 Results

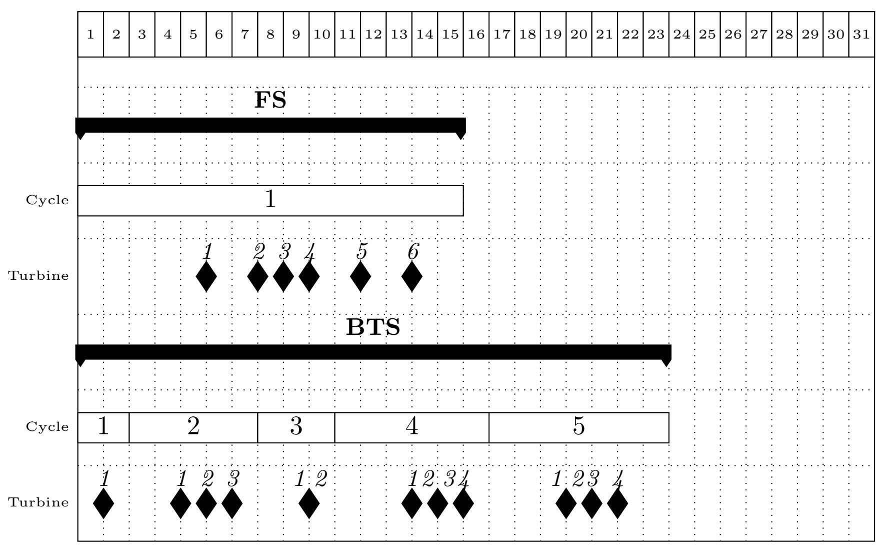

Fig. 1. Gantt chart presenting optimal installation schedule (Sol. 1.1 in Tab. 3) from OWF 1.

Results from the first set of experiments, with $|V| = 3$, are summarized in Tab. 3.

For OWF 1, with 20 turbines and 1 month time horizon, the CPLEX solver finds the optimal solution in 4 seconds with a total cost of \$ $11,106,600$ (see Sol. 1.1 in Tab. 3). The optimal vessel choice is a combination of the BTS and the FS operating from Port 3.

The timing for turbine installations is presented in a Gantt chart (see Fig. 1). The top of the chart represents time, and the duration of each vessel charter period is represented by the black lines. The white boxes with numbers represent cycle durations, and the black milestones, along with the numbers above, represent the start of installation of turbines on a given cycle. Note that most cycles are completed without fully loading the vessels, which is also the case in larger instances.

In OWF 2, we consider 40 turbines and a 3 months time horizon. The CPLEX solver has a harder time finding and/or proving an optimal solution, compared to OWF 1. A feasible solution is obtained within seconds.

After running for $20,000$ seconds, an optimal solution is not proven. The best feasible solution obtained is an upper bound to our minimization problem. Because the CPLEX solver is a branch-and-bound algorithm, we also obtain a lower bound to the problem. The difference between these two bounds compared to the best feasible solution is referred to as the *optimality gap*: The maximum potential improvement in the objective function value in the optimal solution. The best upper bound may very well be the optimal solution even though an optimality gap exists, because the potential reduction in costs may not be feasible.

An optimality gap of 12.4 % is obtained in OWF 2 with a combination of the BTS and the UTS operating from Port 3, and the objective cost measures \$ $19,639,480$ (see Sol. 2.1 in Tab. 3).

For OWF 3, with 100 turbines and 5 months time horizon, no optimal solution is proven within a time frame of $30,000$ seconds. After $30,000$ seconds, an optimality gap of 30.5 % is realized, and the total costs measure \$ $47,858,700$ (see Sol. 3.1 in Tab. 3). In this solution, all strategies are mobilized operating from Port 3. The FS is chartered longest and assigned most turbine installations.

Table 3. Results from OWF 1,2 and 3. The fourth column represents the total number of turbines installed with vessel $v \in V$.

OWF	Sol.	Objective	Turbines			Port	CPU time/Gap
			FS	BTS	UTS		
1	1.1	\$ 11,106,600	6	14	0	3	4 s/0.0 %
2	2.1	\$ 19,639,480	0	10	30	3	20,000 s/12.4 %
3	3.1	\$ 47,858,700	38	36	26	3	30,000 s/30.5 %

Results from the second set of experiments, where $|V| = 6$, are summarized in Tab. 4.

The optimal solution for OWF 1 is found after 76 seconds, and total costs are reduced to \$ $10,958,000$ (see Sol. 1.2 in Tab. 4). The FS is no longer optimal, and the BTS is duplicated, still operating from Port 3. All vessel operations in the duplicated solution happen within the same weather windows.

If we shorten all weather windows for installation operations for the BTS by one working day, the optimal solution is found after 103 seconds (see Sol. 1.3 in

Tab. 4). The UTS is duplicated with a total project cost increase of 5.4 % from Sol. 1.2. In this case, it proves optimal to operate from Port 1.

If we decrease the charter rate of the UTS to $ 160,000 /day (−11 %) and the mobilisation cost to $ 800,000, the optimal solution is found after 13 seconds, and the total costs are reduced by 5.2 % from Sol. 1.2 (see Sol. 1.4 in Tab. 4). The UTS is duplicated with the same schedule as Sol. 1.3 operating from Port 1.

With the possibility of duplications of identical vessels in OWF 2, the optimality gap reaches 7.2 % after 20,000 seconds, and the total costs sum up to $ 19,204,740 (see Sol. 2.2 in Tab. 4). Note that Sol. 2.2 has a lower objective and a lower optimality gap compared to Sol. 2.1 (see Tab. 3), even though the instance is larger.

Since the FS is not mobilized in OWF 2, we try to simplify the instance by eliminating the FS entirely (we impose $\gamma_{\mathrm{FS}} = 0$). In this case, optimality is proven for OWF 2 after 6,000 seconds, and the objective is reduced by 1.0 % compared to Sol. 2.2 (see Sol. 2.3 in Tab. 4).

For OWF 3, a feasible solution is found after 2,200 seconds. After 30,000 seconds, this solution is improved by 4.5 % and has a cost of $ 51,216,768 with an optimality gap of 34.4 % (see Sol. 3.2 in Tab. 4).

In OWF 3, no feasible solution is found after 30,000 seconds for only the FS ($\gamma_{\mathrm{BTS}} = \gamma_{\mathrm{UTS}} = 0$). By using only the BTS ($\gamma_{\mathrm{FS}} = \gamma_{\mathrm{UTS}} = 0$ is imposed), the total costs measure $ 55,045,400 with an optimality gap of 39.0 % after 30,000 seconds (see Sol. 3.3 in Tab. 4). For only the UTS ($\gamma_{\mathrm{FS}} = \gamma_{\mathrm{BTS}} = 0$), the total costs drop below Sol. 3.1 (see Tab. 3) with an objective of $ 44,673,060, and an optimality gap of 6.0 % after 30,000 seconds (see Sol. 3.4 in Tab. 4).

Table 4. Results from OWF 1,2 and 3 with possibility of duplication. The fourth column represents the total number of turbines installed with vessel $v \in V$.

OWF	Sol.	Objective	Turbines						Port	CPU time/Gap
			FS1	FS2	BTS1	BTS2	UTS1	UTS2		
1	1.2	$ 10,958,000	0	0	10	10	0	0	3	76 s/0.0 %
	1.3	$ 11,555,200	0	0	0	0	10	10	1	103 s/0.0 %
	1.4	$ 10,382,400	0	0	0	0	10	10	1	13 s/0.0 %
2	2.2	$ 19,204,740	0	0	14	13	13	0	3	20,000 s/7.2 %
	2.3	$ 19,019,520	-	-	13	13	14	0	3	6,000 s/0.0 %
3	3.2	$ 51,216,768	25	29	5	11	29	0	3	30,000 s/34.4 %
	3.3	$ 55,045,400	-	-	45	55	-	-	3	30,000 s/39.0 %
	3.4	$ 44,673,060	-	-	-	-	54	46	3	30,000 s/6.0 %

4.3 Discussion

Because the model is deterministic, uncertainty is not considered in each instance. The trait of not dealing with uncertainty explicitly is demonstrated to be unfortunate through OWF 1 (see Sol. 1.2-1.4 in Tab. 4). With a small change in uncertain input data concerning weather and costs, the solution output is altered completely in terms of both port and vessel decisions. Conclusions drawn to aid strategic decisions from a single instance are thus rather speculative, even with optimality proven.

The seemingly nice benefit of being able to carry many wind turbines per trip turns out to be of small significance, since most cycles are performed without fully loading the vessels. This may be a consequence of the weather sensitive installation lifts being the bottlenecks of the process, as concluded by [2].

The suggested port choice for most instances is Port 3 with highest fixed costs and shortest travel distance to wind farm. The port decision changes from Port 3 to Port 1 in OWF 1 for instances where the UTS is proven the optimal strategy. This is probably due to longer weather windows for the UTS for installation operations, which makes longer transits and lower port handling costs a preferable choice. Potential growth of port handling costs with OWF size is not considered.

The UTS, with the benefit of long weather windows, seems to be a good option for large farms in OWF 3 (see Sol. 3.4 in Tab. 4). However, OWF 3 also show that including more vessel possibilities for the same wind farm does not necessarily produce better solutions (compare Sol. 3.1 in Tab. 3 and Sol. 3.2 in Tab. 4). Thus, our ability to draw conclusions from solutions obtained without proving optimality might be limited, although in some cases (see Sol. 2.2-2.3 in Tab. 4), the proven optimal solution (Sol. 2.3) has the same port and vessel fleet as the solution obtained without proving optimality (Sol. 2.2).

5 Conclusions

The instances in Section 4 can be used to support arguments for which factors are the most critical during the installation of OWFs, and which vessel and port strategy is the preferable choice for a specific OWF. Several instances ought to be implemented for the same OWF to somehow deal with uncertainty.

The framework of the problem in this model calls for drastic simplifications if large instances are to be tackled with an exact solver in a reasonable time frame. Further work can be done on developing heuristic methods to solve instances of the current model, however, proving optimality might still be challenging. Stochastic extensions will further complicate the model, so on a strategic and aggregated level, several scenario analyses may be a better alternative to aid the project decisions considered in this work.

Considering smaller fractions of a large wind farm can be a way of proving optimality with the CPLEX solver. Whether the strategic choices are altered when considering large wind farms in an aggregated versus fractionated manner, depends on how the different input data scale for growing instances, especially port handling costs.

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