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A metaheuristic solution method for optimizing vessel fleet size and mix for maintenance operations at offshore wind farms under uncertainty

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Abstract

Maintenance operations at offshore wind farms are challenging due to the offshore element; maintenance technicians and spare parts need to be transported from an onshore port or offshore station to the individual wind farm components in need of maintenance. The vessel resources needed to support these maintenance tasks constitute a major part of the total maintenance costs, and hence up-keeping an optimal vessel fleet and corresponding deployment is essential to reduce cost-of-energy. This paper introduces a metaheuristic solution method to determine cost-efficient vessel fleets to support maintenance tasks at offshore wind farms under uncertainty. It considers weather conditions and failures leading to corrective maintenance tasks as stochastic parameters, and evaluates candidate solutions by a simulation program. The solution method has been incorporated in a decision support tool. Computational experiments, including comparison of results with an exact solution method, illustrate that the decision support tool can be used to provide near-optimal solutions within acceptable computational time.

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Keywords: offshore wind; operation and maintenance; operations research; fleet composition; decision support; metaheuristic

1. Introduction

The costs of vessels, helicopters and related infrastructure to support operation and maintenance (O&M) tasks are amongst the largest contributors to the total costs of the operational phase of an offshore wind farm. For a typical offshore wind turbine with a life span of twenty years, the total O&M costs account for around 20 % to 35 % of the total life cycle costs [1].

Maintenance logistics is an important competitive factor in the offshore wind energy industry having a significant impact on the profitability of offshore wind projects [2]. For the time being the offshore wind energy industry is dependent on financial support to be profitable. One means to reduce the costs of maintenance logistics is to select

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cost-efficient vessel fleets to support the O&M tasks. In this paper, vessel is used as a general term and include both potential vessel and helicopter resources.

In the existing literature, there are only a few studies on the use of optimization models to determine optimal vessel fleets for maintenance operations at offshore wind farms. A deterministic model was proposed in [3], that was extended to a stochastic model in [4]. Stochastic optimization models have also been proposed in [5] and [6].

Most of the related existing literature and decision support tools to evaluate maintenance logistics are based on simulation models. A review of decision support systems for offshore wind farms with an emphasis on O&M strategies is provided in [7], and a comparison of some simulation models and the optimization model proposed in [6] is presented in [8].

This paper presents a new metaheuristic solution method for the offshore wind O&M vessel fleet optimization problem. The method consists of two steps: First a quick construction heuristic is used to generate a feasible starting solution. Then a local search improvement algorithm will evaluate the neighborhood solutions of the starting solution. The method considers weather conditions and failures resulting in corrective maintenance tasks as stochastic parameters and evaluates each candidate solutions by a simulation program. It has been incorporated into a decision support tool (DST) that can be used by actors in the offshore wind industry to find and evaluate optimal vessel resources for the O&M phase for offshore wind farms.

The rest of the paper is organized as follows: Section 2 provides a problem description and a verbal description of the mathematical problem formulation that the metaheuristic solution method is based upon. Then Section 3 presents the metaheuristic solution methodology and gives a brief description of the decision support tool in which it has been incorporated. In Section 4 a computational study is presented before the paper is concluded in Section 5.

2. Problem description and formulation

An offshore wind farm is described by its distance to onshore ports, its internal travel distances (used to calculate average travel distance between turbines for execution of maintenance operations), number of turbines, installed capacity per turbine and the turbines' power curve. The problem considered is to determine vessel fleet size and mix to support the maintenance operations at a wind farm. A planning horizon of one year is considered, and the vessel resources may be long-term chartered, i.e. for the whole year, or short-term chartered where a charter term is defined to be one calendar month.

Maintenance operations at a wind farm can be split in two main categories: Preventive and corrective maintenance tasks. Preventive tasks are carried out at predetermined intervals or according to prescribed criteria from turbine manufacturers, and intend to reduce the probability of failure or the degradation of the function of an item. These types of maintenance tasks are typically given a long time window for execution, e.g. 3-6 months (maintenance campaign). It is assumed that the turbines need to be shut down for maintenance during execution of preventive maintenance tasks, and hence a downtime cost is induced equal to the lost income due to lost energy production. Corrective tasks need to be executed whenever there is a component failure resulting in a need for repair or replacement. The need for execution of corrective maintenance tasks will not be known until a failure occurs, and it is assumed that such component failures result in system malfunction, e.g. a component failure at a turbine will result in a turbine shutdown. Hence, a downtime cost is induced for these maintenance tasks equal to the lost income due to lost energy production from the time of the failure until the corrective task has been executed.

Maintenance tasks will require up to three different types of activities requiring vessel resources: Transportation of maintenance technicians, transportation of spare-parts and equipment, and lifting activities. For tasks requiring only maintenance technicians, i.e. a vessel resource does not need to be present at the turbine to execute the task, a vessel resource can support several tasks in parallel by dropping-off teams of maintenance technicians at the turbines and return to pick-up the teams upon finalization of the work or at the end of the work shift. Discussions with industry regarding safety regulations suggests that the limit of such parallel tasks should be four. A penalty cost applies for all maintenance tasks not executed within the planning horizon. To account for end-effects, maintenance tasks that are to be executed shortly before the end of the planning horizon (year) may be executed at the start of the planning horizon.

Potential vessel fleets used to support O&M tasks at offshore wind farms consist of a mix of vessels and helicopters with different operational criteria. All vessel resources need to be associated with a maintenance base that can be e.g. an onshore port or an offshore station. Onshore ports and offshore stations have a given distance to the offshore wind farm site, a maintenance technician availability, and compatibilities with vessel resources, i.e. not all bases can accommodate all types of vessel resources. The vessel resources' operational criteria determine which maintenance tasks they can support. These consist of the capacities of the resource, e.g. personnel transportation capacity, equipment and spare part carrying capacity, lifting capacity for e.g. replacing major components, and weather criteria; in which wave heights and wind speeds the vessel can be used to support maintenance tasks.

Weather conditions and component failures resulting in corrective maintenance tasks are highly uncertain parameters that will affect the optimal vessel fleet size and mix. Hence, these parameters are treated as stochastic. Weather input (wind speed and wave height) is provided as time series, and have an impact on accessibility to the offshore wind farm and the power generation that determines the downtime costs. A maintenance task can only be executed if there is a sufficiently long weather window for its execution. Safety regulations require that maintenance technicians can be picked-up by a vessel at all times working on a turbine, hence limited weather windows where technicians are dropped-off whilst acceptable weather conditions and left at the turbine during worse weather conditions for picking-up when weather conditions improve cannot be utilized. Failures are provided as yearly failure rates for the probability of a turbine experiencing a failure resulting in a given type of corrective maintenance task during a year.

A two-stage stochastic mathematical model formulation for this problem is proposed in [6]. The first-stage decision variables in the formulation are how many of each vessel resource to charter on long-term and on short-term contracts, which maintenance bases should be used, and which maintenance base each vessel resource should be deployed at. The second-stage decision variables are which maintenance patterns the vessel resources should execute at which days during the planning horizon. The objective function minimizes the total cost of operating the offshore wind farm during the planning horizon; the fixed costs of maintenance bases, time charter costs of vessel resources, variable costs of executing maintenance patterns, downtime costs and penalty costs of any maintenance tasks that are not executed within the planning horizon.

First-stage constraints consist of ensuring that the total number of vessels operating from a maintenance base does not exceed the capacity of that base, that any maintenance bases and vessel resources that need to be in the solution are in the solution, and that the number of vessels being time-chartered does not exceed the number of available vessels. Second-stage constraints consist of ensuring that all preventive and corrective maintenance tasks are either executed during the planning horizon or are given a penalty cost, that all corrective maintenance tasks are mapped to a given time period and vessel resource, that there are vessels available to execute the used maintenance patterns, and that vessels only use maintenance bases that are part of the solutions and that the maximum number of maintenance technicians available at the bases is not exceeded.

The metaheuristic solution method proposed in this paper is based on this above described stochastic mathematical model formulation. For a thorough description of the model the reader is referred to [6].

3. Solution method

This section describes the metaheuristic that is used to solve the problem of determining optimal vessel fleet size and mix for maintenance operations at offshore wind farms. In Section 3.1 the metaheuristic framework is provided. Then the decision support tool in which the metaheuristic has been implemented is introduced in Section 3.2.

3.1. The metaheuristic framework

To provide useful decision support, the implemented algorithms solving the underlying decision problem need to be able to provide solutions for realistically sized problem instances within reasonable computational times. Hence, an efficient metaheuristic approach is proposed for the vessel fleet size and mix problem for maintenance operations at offshore wind farms.

The metaheuristic approach is a version of a greedy randomized adaptive search procedure - GRASP [9]. It consists of first constructing initial feasible solutions to the problem by a greedy randomized algorithm. A solution to the fleet size and mix problem consists of a feasible fleet of maintenance vessels and their corresponding maintenance bases. After constructing feasible solutions, the solutions are improved by a local search procedure. The implemented local search procedure is a version of a tabu search [10], and explores neighborhood solutions to an initial solution. Neighborhood solutions are defined by a number of neighborhood operators that defines changes to the vessel fleet

Algorithm 1 GRASP procedure

```
input problem instance
initialize best solution
while stopping criterion not met do
    construct greedy randomized solution - initial solution
    perform local search procedure on initial solution - generate candidate solutions
    update best solution with best solution of current best, initial and candidate solutions
end while
return best solution
```

size and mix of the initial solution. An overall pseudo-code for the GRASP procedure is shown in Algorithm 1. The stopping criterion for the procedure is the number of iterations, i.e. the procedure terminates after a given, user-specified number of iterations.

In the local search procedure, the following neighborhood operators are used:

- Add vessel long-term: Add one feasible vessel on long-term charter to the solution.
- Remove vessel long-term: Remove one vessel on long-term charter from the solution.
- Add vessel short-term: Add one feasible vessel on short-term charter for one charter period to the solution.
- Remove vessel short-term: Remove one vessel on short-term charter for one charter period from the solution.
- Swap bases: Swap vessels associated with a maintenance base in the solution to a different maintenance base.
- Swap vessels short-term 1: Remove one vessel on short-term charter in a charter period, and replace it with a different vessel type on short-term charter.
- Swap vessels short-term 2: Remove one vessel on short-term charter in a charter period, and insert it in a different charter period.
- Swap vessels: Remove a vessel on long-term charter in the solution, and replace it with a different vessel type on long-term charter.
- Remove base: Remove a maintenance base and the vessels associated with it from the solution.

The initial feasible solution and its neighborhood solutions are called candidate solutions. Each candidate solution is evaluated through a simulation procedure that consists of a scenario generator that generates a number of weather data sets and corrective maintenance tasks sets, and a calculator that calculates the objective function value of the candidate solution for a given weather data and corrective maintenance task set. The evaluation of a candidate solution is then the average sum of the objective function values over all scenarios.

A flow chart of the simulation procedure in the calculator is shown in Figure 1. The procedure iterates through all days in the planning horizon, adds any new corrective maintenance tasks on a day to the problem and any new vessels chartered on short-term contracts. Then it iterates through all available vessels, checks for availability of maintenance technicians and weather window before the vessel can start the execution of maintenance tasks. Corrective maintenance tasks are prioritized, hence any corrective tasks that a vessel can execute are executed before any preventive maintenance tasks. Maintenance tasks can be executed in parallel, i.e. the vessel drops-off technicians on one turbine before proceeding to next turbine that requires maintenance. The procedure continues upon finalizing the iterations over all available vessels and all days in the planning horizon.

The overall architecture of the metaheuristic framework is shown in Figure 2.

3.2. Decision support tool

The metaheuristic framework presented above has been implemented in a decision support tool - HOWLOG - Heuristic solver for Offshore Wind o&m LOGistic resource optimization. As shown in Figure 2 input and output are provided in Excel Workbooks and weather data are provided from text-files. Figure 3 gives an overview of the input and output data.

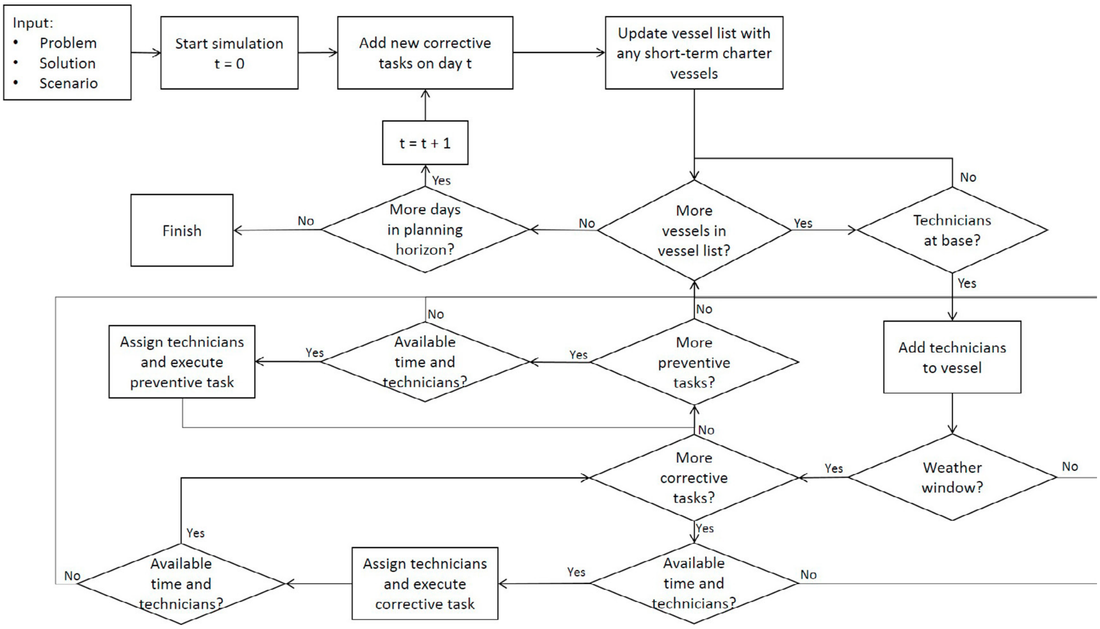

Fig. 1. Flow chart of the simulation procedure in the calculator

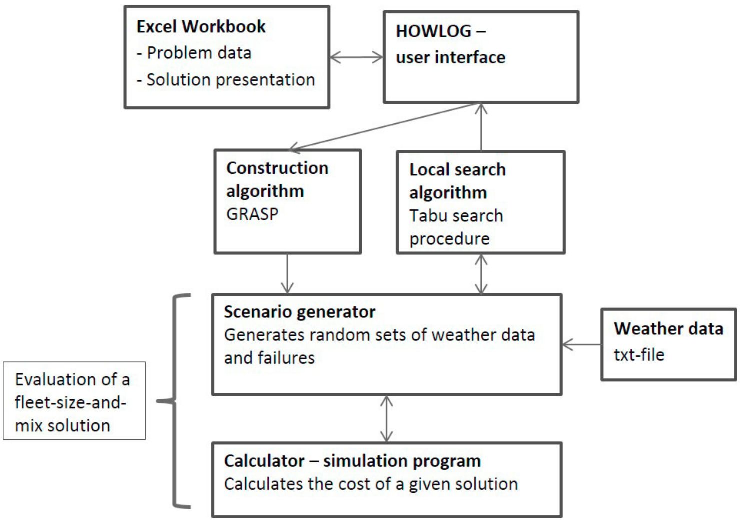

Fig. 2. General overview of the metaheuristic framework

Through an application the user selects the Excel Workbook that contains the input data for the problem to be solved. If readable weather files on a yearly basis has not been generated, the user can generate these. Then the user can choose between three different options:

1. Quick search - 10 iterations
2. Medium search - 25 iterations
3. Extended search - 50 iterations

When the program has finished execution, the solution is visible in the application and can be exported to an Excel Workbook.

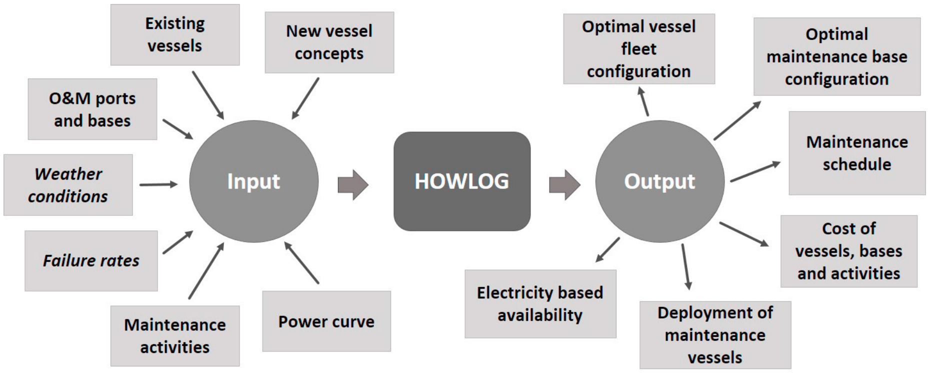

Fig. 3. HOWLOG - input and output overview

4. Computational study

The metaheuristic presented in the previous section has been tested on one problem instance. The results are compared with the ones from the exact solution method presented in [6]. The solution method from [6] is a stochastic mathematical programming model, formulated as its scenario-tree equivalent, and hence an optimal solution will be evaluated directly over the input scenarios. This model also optimize on when to execute the maintenance tasks, whereas the metaheuristic procedure uses simpler criteria for when to execute the maintenance tasks, as shown in Figure 1.

The problem instance used for testing is presented in Section 4.1 and results and discussions are provided in Section 4.2.

4.1. Problem instance

The problem instance is the one presented and used in [8]. The offshore wind farm consists of 80 3MW turbines located 50 km from an onshore maintenance base. There is one type of preventive maintenance task, requiring three technicians, with a total duration of 60 hours that should be executed on all 80 turbines. Three types of corrective maintenance tasks are defined, with expected number of failures pr. turbine pr. year at 7.5, 3 and 0.825. Expected number of hours needed to execute the corrective maintenance tasks and the required number of technicians (in brackets) are 3(2), 7.5(2) and 7.5(3), respectively. Weather input data are provided as historical weather time series from the FINO 1 offshore research platform for the years 2004 - 2011 [11]. An overview of available vessel resources is provided in Table 1.

Table 1. Problem instance - available vessel resources

Vessel type name	Hs limit [m]	Transfer speed [knots]	Day rate [GBP]	Technician space	Access time [min]	# available vessels
Crew transfer vessel (CTV)	1.5	20	1 750	12	15	5
Surface effect ship (SES)	2.0	35	5 000	12	15	5
Small accommodation vessel (SAV)	2.0	20	12 500	12	15	1
Mini mother vessel (MM)	2.5	14	25 000	16	30	1
Daughter vessel (DM)	1.2	16	N/A	6	15	2

4.2. Results and discussion

To obtain the results presented in this section, settings for the metaheuristic procedure (GRASP) were 10 iterations and 30 simulations on each candidate solution, and for the exact stochastic optimization model presented in [6] (EXACT) 5 scenarios are used. The GRASP method has been implemented in Java, and the EXACT method has been implemented in the Mosel language and solved by FICO^{TM} Xpress version 7.6. The accepted optimality gap for the EXACT method was set to 1.0 %. All results were obtained on a laptop with an Intel Core i7-4600U 2.10 GHz processor and 16 GB RAM under Windows.

Table 2. Computational results.

	GRASP	EXACT
Vessel fleet	2 SES	2 SES
Total cost	13 438 078	13 318 186
Base cost	0	0
Vessel cost	3 650 000	3 650 000
Voyage cost	2 098 533	2 016 700
Downtime cost	7 689 544	7 651 486
Penalty cost	0	0
Electricity based availability	92.96 %	93.02 %
Computational time [s]	144	7 961

The results are shown in Table 2. The vessel fleet for both solution methods were the same: Two vessels of type surface effect ship. There are some variations in the costs of the two solutions, which is as expected due to the stochastic input parameters and the different methods for determining when to execute the maintenance tasks. The computational time for the GRASP method was significantly less than for the EXACT solution method (144 seconds vs 7961), illustrating how the GRASP method can provide decision support within short computational time.

An analysis was also conducted to illustrate the necessity of using a stochastic approach when evaluating vessel fleet size and mix for maintenance operations at offshore wind farms: Both the GRASP and the EXACT methods were run deterministically for each weather input year. It should be noted that the occurrence of corrective maintenance tasks is still drawn individually, i.e. the input of corrective maintenance tasks will vary for each problem instance that is run, creating some randomness to the solutions. The results are presented in Table 3.

Table 3. Results deterministic cases - optimal vessel fleets.

	2004	2005	2006	2007	2008	2009	2010	2011
GRASP	2 SES	2 SES	2 SES	2 SES	2 SES	1 CTV, 1 SES	1 CTV, 1 SES	3 SES
EXACT	2 SES	2 SES	2 SES	1 SES, 1 SAV	2 SES	1 CTV, 1 SES	1 CTV, 1 SES	3 SES

As can be seen from the results in Table 3, the solution of two vessels of type surface effect ship is not the optimal one for all weather input years. The results indicate that years 2009 and 2010 are somewhat better weather years that allow for a fleet with a less costly vessel with lower Hs limit and transfer speed, while 2011 is a worse weather year where optimally one more surface effect vessel should be added to the vessel fleet. The results are almost identical for the two solution methods, apart from one year, indicating that the GRASP methodology is a good substitute for the EXACT solution method.

5. Conclusions

This paper presented a metaheuristic solution method for optimization of the vessel fleet size and mix for maintenance operations at offshore wind farms. This optimization problem also involves determining the vessel fleet's deployment, and hence the expected total costs of O&M and expected electricity-based availability of the wind farm during the considered planning horizon.

The metaheuristic solution method is a version of a greedy randomized adaptive search procedure - GRASP - and consists of first generating initial solutions by a greedy randomized procedure and then searching for improvements to the solutions by a local search procedure. The proposed local search procedure is a version of a tabu search. Each candidate solution is evaluated by a simulation program that calculates the expected value of the solution over a given number of scenarios consisting of variations in weather conditions and corrective maintenance tasks.

The GRASP and tabu search approach was selected as it is difficult to create good neighborhood operators for this vessel fleet size and mix problem. The pool of potential vessel resources that may be selected as part of a solution is heterogeneous and there are, for most problem instances, huge variations in vessel costs and workloads. The GRASP methodology generates several starting solutions and hence creates a diversified search over a larger part of the solution space.

The proposed solution method has been incorporated in a decision support tool - HOWLOG. A computational study that compared the proposed methodology with an exact solution method showed that the methodology can propose cost-efficient vessel fleets within short computational time.

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