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Bi-objective optimisation model for installation scheduling in offshore wind farms

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ABSTRACT

A bi-objective optimisation using a compromise programming approach is proposed for installation scheduling of an offshore wind farm. As the installation cost and the completion period of the installation are important aspects in the construction of an offshore wind farm, the proposed method is used to deal with those conflicting objectives. We develop a mathematical model using integer linear programming (ILP) to determine the optimal installation schedule considering several constraints such as weather condition and the availability of vessels. We suggest two approaches to deal with the multi-objective installation scheduling problem, namely compromise programming with exact method and with metaheuristic techniques. In the exact method the problem is solved by CPLEX whereas in the metaheuristic approach we propose Variable Neighbourhood Search (VNS) and Simulated Annealing (SA). Moreover, greedy algorithms and a local search for solving the scheduling problem are introduced. Two generated datasets are used for testing our approaches. The computational experiments show that the proposed metaheuristic approaches produce interesting results as the optimal solution for some cases is obtained.

1. Introduction

Wind power is a promising electricity generation source as it is renewable and can hence contribute to the reduction of carbon gas emissions. As the power output from a wind turbine is a function of wind speed, a wind farm should be located in an area that has strong and steady wind. The number of global offshore wind farms is rapidly increasing annually as the average of wind speed at sea is superior compared to that of onshore. Additionally, siting wind farms offshore can alleviate some of the land use and social concerns found in onshore wind farms. According to European Wind Energy Association [14], in the European Union (EU), the cumulative installed capacity of offshore wind power increased significantly to 6600 MW in year 2013 from 532 MW (MW) in year 2003.

However, CAPEX (capital expenditure) and OPEX (operating expenditure) costs of offshore wind turbine are much higher than those of onshore ones. At sea a wind turbine is more difficult to install and maintain so more resources and infrastructures are needed; therefore the cost spent on offshore one is much higher. The installation/construction phase of an offshore wind farm is very challenging as heavy equipment and costly vessels are required. Based on the Renewables Advisory Board [37], the installation and commissioning phase makes up 26% of CAPEX cost of which vessel chartering costs contribute the biggest portion.

A wind turbine mainly consists of three components namely sub-structure (foundation and transition piece), cable, and top-structure (tower, nacelle, and blades). Sub- and top-structures are usually installed by a self-elevating vessel including a barge and a self-propelled installation vessel. In barge installation, a barge transports sub- or top-structures while the installation vessel positioned at site will conduct the installation. In self-propelled, an installation vessel will pick up sub- or top-structures at the staging area (port), and then return to site to do the installation. For cable (inner-array cable) installation, the most common methods involve the use of an ROV (Remotely Operated Vehicle) operated by either the main installation vessel or a specialized cable-laying vessel [23].

The weather conditions (such as wind speed and wave height) and the vessel availability are the main factors that affect the performance of the installation process. The delay in installing wind turbines is mainly due to those factors and a one-day delay will cause a significant financial loss. For safety reasons, the installation must be conducted in the period when the required weather conditions are met. The sub-structure and cable can be installed with relatively stronger wind speeds, while the top-structure requires calmer weather. As good weather periods are limited, this leads to a massive stockpiling of material and resources in the port or on

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board of the vessel to exploit these periods [40]. Here, the schedule of the installation is very important for determining suitable target inventories for the whole supply chain.

When scheduling the installation of wind turbine, the planner usually seeks the best configuration to complete the project as soon as possible at minimum cost. However, it is not easy to achieve as the completion installation period/date and installation cost are conflicting objectives. For example in Northern Europe, to minimise the installation cost the installation of top-structures has to wait until spring or summer when the weather is relatively calm, otherwise in winter the installation time of a top-structure will take longer which results in the increase of the installation cost. In this paper, we are investigating the installation scheduling of offshore wind farm in the presence of two conflicting objectives namely total installation cost and total completion period. To the best of our knowledge, there is no paper in the literature studying such a problem.

The main contributions of this paper include: (i) a mathematical model of the installation scheduling problem, (ii) greedy algorithms and a local search for finding the best schedule that minimises total installation cost or total completion period, (iii) application and comparison of VNS and SA for solving the scheduling problems.

The paper is organized as follows: Section 2 presents a brief review of the past efforts at offshore wind installation mainly concentrating on the scheduling problem. Section 3 gives a description of our approach in developing a mathematical model of installation scheduling followed by an explanation of compromise programming method for solving the bi-objective scheduling problem. Our meta-heuristic methods (VNS and SA) as well as the overall algorithms are presented in Section 4. Section 5 gives computational results using generated data. A summary of our findings and some avenues for future research are provided in the last section.

2. Past efforts at offshore wind installation

This section presents an overview of past efforts at offshore wind farm focussing on installation scheduling problem. We found four papers in the literature related to installation scheduling problem for offshore wind farm. Scholz-Reiter et al. [40] introduced a mathematical model using mixed integer linear programming (MILP) to obtain the optimal installation schedule with the objective to reduce vessel operation times considering weather conditions. Their model is to schedule one vessel where the vessel can install both sub- and top-structures. The model also only runs for short planning horizon.

Scholz-Reiter et al. [41] proposed a heuristic technique to overcome limitations of their previous model [40]. The heuristics approach is able to solve relatively large problems with longer time horizons, multiple vessels and a broader variety of weather conditions. Their computational experiments show that the proposed approach produces competitive results.

A simulation approach for determining the optimised configuration of a single-echelon inventory system for offshore installations of wind turbines was investigated by Lütjen and Karimi [28]. They also present a reactive scheduling heuristic based on the model in Scholz-Reiter et al. [41]. They found that it is feasible to determine optimised configurations of the logistic system.

A mathematical model dealing with the aggregated installation planning problem for medium planning horizon is introduced by Ait-Alla et al. [1]. Their model seeks the optimal aggregated schedule that minimises the total installation costs. The chartering costs and weather operation constraints for different vessel types are considered in the model.

Other interesting topic related to the scheduling problem of an offshore wind farm is offshore maintenance scheduling. Maintenance scheduling aims to produce a detailed schedule of maintenance tasks that have to be performed within a certain period considering the availability of several resources including vessels, spare parts, and crews. Besnard et al. [7] investigated an opportunistic maintenance optimization model taking into account wind forecasts and corrective maintenance activities. Discrete event-based simulation models of maintenance scheduling were studied by Pérez et al. [36], Byon et al. [10], and Pérez et al. [34].

Kovács et al. [26] developed a mathematical model (MILP) to determine the best time for maintenance operations considering the availability of the resources and the performance of the wind turbine. Besnard et al. [8] enhanced their earlier model [7] where uncertainty weather condition is taken into account so the problem becomes a stochastic optimisation problem. A formulation of mathematical model to optimise maintenance cost was introduced by Parikh [32]. The added value of a prognostic maintenance policy was quantified by Van Horenbeek et al. [44].

Long- and short-terms scheduling models for wind power integrated systems were proposed by Wang et al. [45] where the former model involves maintenance scheduling and energy allocation, while the latter finds hourly power output. Wu et al. [47] studied the maintenance scheduling model taking into account peak regulation pressure balance. Zhang et al. [49] investigated an optimal preventive maintenance scheduling model for minimising the overall downtime energy losses taking into account weather conditions, crews, transportation, and tooling infrastructure. Maintenance scheduling of large-scale wind power considering peak shaving was studied by Zhang et al. [50].

A simulation model for optimising maintenance schedule was implemented by Benmessaoud et al. [6] which is used to analyse the influence of maintenance on the performance of a wind farm. A stochastic petri-net model for maintenance planning was proposed by Dos Santos et al. [12] considering the availability of vessels, crews, and spare parts. Ge et al. [18] studied a long-term scheduling method for wind-hydro-thermal power systems. Pan et al. [31] proposed a long-term multi-objective optimisation dispatch and its evaluation in wind integrated power systems involving maintenance scheduling, unit commitment, and power output. An integrated planning and scheduling maintenance method was investigated by Pattison et al. [33]. Perez-Canton and Rubio-Romero [35] put forward a model for the preventive maintenance scheduling of power plants including wind farms where the aim is to maximise the system reliability.

Stålhane et al. [43] and Dai et al. [11] investigated the problem of finding the optimal routes and schedules for a fleet of vessels that are to perform maintenance tasks at an offshore wind farm. Recently, a comprehensive review related to maintenance logistics in offshore wind energy can be found in Shafiee [42].

3. Installation scheduling model for offshore wind farm

Offshore wind turbines can be installed using several scenarios. Fig. 1(a) shows an approach to install the turbines which is considered in this paper. The components (cables, top- and sub-structures) are prepared at the port which is usually the nearest one to the wind farm site. The installation vessel picks up the components and transports them to the wind farm site. The vessel will also perform the installation which may take several days. The recent vessel can transport top-structure components (tower, nacelle, and blades) for more than six turbines. Once the installation process on the site has been completed, the vessel may return to the port again to pick up other components. Fig. 1(b) illustrates the installation vessel, which is designed to transport and install more than four top-structures