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Layout optimisation for an installation port of an offshore wind farm

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ABSTRACT

This paper investigates a port layout problem, where the layout of an installation port for an offshore wind farm needs to be generated in an efficient way so as to minimise the transportation cost of main components of an offshore wind turbine within the port. Two mixed integer linear programming (MILP) models are established to configure the optimal port layout, where the shapes of subareas that need to be located in the port are rectangular with several possible dimensional configurations to select from and the shape of the port area can be treated as either a convex or a concave polygon. The MILPs can be solved to optimality for small-sized problems. Matheuristic approaches based on Variable Neighbourhood Search (VNS) and an exact method (MILP) are also proposed to find solutions for medium-sized problems. The methods are assessed using randomly generated data sets. In addition, the area of a proposed Scottish port is used as a case study. The results obtained from the computational experiments validate the effectiveness of the proposed matheuristic approaches.

1. Introduction

Within two decades of the installation of the first offshore wind farm (OWF) in 1991, the offshore wind industry has experienced a substantial growth in terms of the number of projects and the capacity per project. Although in the late 1990 s single wind turbines (WT) with power ratings less than hundreds of kilowatts were installed, today offshore wind farms are planned with capacities above 1 gigawatt. Thus, it is fair to say that OWF have generation capacities comparable to that of existing conventional power plants (Perveen, Kishor, & Mohanty, 2014). By the end of 2014, there were 25 gigawatts of consented offshore wind projects in Europe (EWEA, 2015); this remarkable growth in the industry is matched by its significant future potential and also reflects the need of developing ports and onshore infrastructure to effectively support the planned OWFs.

For the development of this industry, ports play a fundamental role and its rapid growth imposes significant requirements on the ports and their characteristics. The efficient installation of an offshore wind farm depends on the proper setup in the port area. If the port's layout and access lanes are ideal, the turnaround time for an installation cycle will not be unnecessarily lengthened. Also efficient layout configuration can result in a significant reduction in the initial investment and in the resultant long term operational costs (Tompkins et al., 1996). The opposite however, will put constraints on all parts of the project (Thomson, 2012).

The wind farm port layout problem has the similarity to the facility layout problem (FLP) and container port layout problems. The port area can be segmented into *subareas*: unloading areas, storage areas, staging areas and loading areas (see Fig. 1). The components (including nacelle, tower and blades) are unloaded at the unloading area along the road of the entrance of the offshore wind port where each component is stored at its respective storage area. The components are then taken to the staging area allocated to each component where further preparation and assembly is performed. Lastly, components are taken to the loading area at the quayside where they will be loaded on the heavy lift vessels and taken offshore. It is recognised that the average container port item is lighter, smaller and more regularly shaped than a wind farm component. The heavy and irregular shaped wind farm components require a platform vehicle with a large array of wheels to transport, which is called Self-propelled modular transport vehicles (SPMT). The unit transportation cost of the SPMT is relatively very expensive. The layout of a port servicing the offshore wind industry should hence be optimised in order to minimise the total transportation cost.

The facility layout problem (FLP) is the placement of the facilities with known dimensions in the plant area to minimize operating cost and maximize system efficiency. FLP exists in various contexts in the literature, e.g., positioning machines in automated manufacturing systems or locating buildings on a factory premises.

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Table 1
The area, aspect ratios and orientation of the subarea *i*.

Subarea *i*	Area	Min aspect ratio	Max aspect ratio	Orientation
Loading area	50,000 metre square	1.12	1.25	Horizontal or vertical

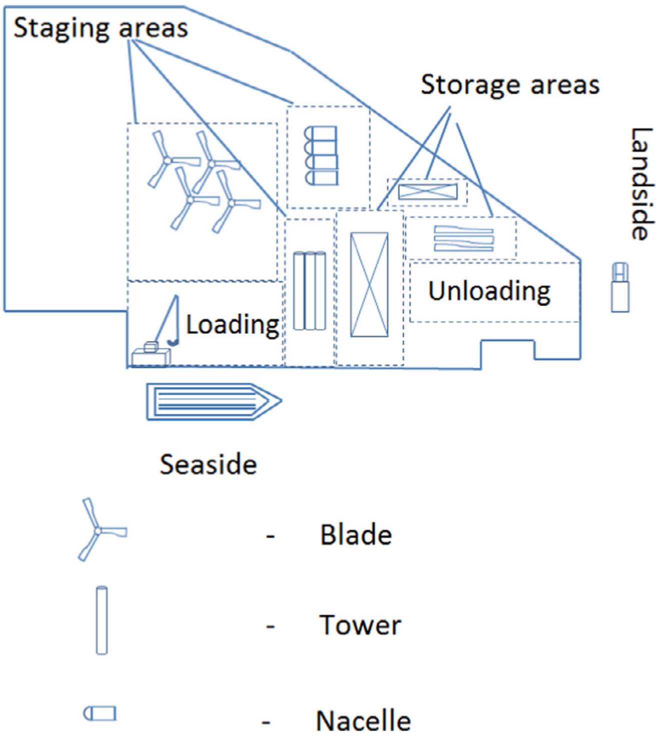

Fig. 1. Schematic top view of an offshore wind farm port layout.

A FLP generally has a set of constraints as follows: (1) all facilities must be located within a given plant area; (2) these facilities must not overlap with one another, and some facilities must be fixed at certain locations or forbidden for being in specific regions (Meller & Gau, 1996). Recent publications on FLP addressed more complicated and realistic constraints, like: (3) the layout must fulfil aspect ratio (height to width or width to height) constraints for the dimension of facilities, because facilities with proper aspect ratios are more practical in real-world applications (Chwif, Barretto, & Moscato, 1998; Tam & Li, 1991). More detailed definition about aspect ratio will be illustrated later; (4) Facilities or the plant are of complicated geometric shapes (Chen, Jiang, Wahab, & Long, 2015; Lee & Kim, 2000); (5) A limited number of models in FLP can accommodate the structure of aisles (Zhang, Savas, Batta, & Nagi, 2009). (6) The layout's efficiency is measured in terms of the closeness rating of the two facilities (Neghabi & Tari, 2016). A more detailed review on FLPs will be provided in Section 2. A solution to the FLP is a layout that specifies the relative location and dimensions of each facility.

In the offshore wind farm port layout problem, both general and specific constraints (1)–(5) in FLP are considered. As shown in Fig. 1, each subarea can be represented as a rectangular block, considering its area, orientation and *aspect ratio* (Tam & Li, 1991). The two orientations considered for each subarea are horizontal or vertical to the port seaside, and according to the offshore wind farm port layout practice, both orientations are allowed for each subarea. The aspect ratio of the subarea is defined as the ratio of the subarea's long side length to its shorter side length. The areas, minimum (Min) and maximum (Max) aspect ratios, and orientation of the subarea *i* are specified in Table 1 as an example.

The feature that the port area may need to be represented as an irregular shape based on its geographic characteristics complicates the FLP problem. For example, some of solution techniques dealing with rectangular shaped facility and/or plant area may not be applicable (Heragu & Kusiak, 1991; Meller, Narayanan, & Vance, 1999), e.g., when a plant area has a rectangular shape, the aspect ratio can be used to restrict the occurrence of an extremely long and narrow facility. However, when a plant area has an arbitrary shape, dealing with aspect ratios is challenging. In the literature, only one study is found in the FLP literature, which dealt with both an irregular shaped plant area and aspect ratio (Chen et al., 2015). The slicing structure (Chen et al., 2015) applied to divide the irregular shape logistics park into several non-overlapping regions is not accurate enough to measure the distance between two subareas in the offshore wind port layout problem considered by this paper.

In this paper, to cope with aspect ratio, aisle and irregular shape of the port area at the same time, the actual lengths and widths of the subarea *i* are predefined by the offshore wind farm port layout decision maker according to the dimensions of the components, aisle area required by the vehicles, aspect ratios and required rotations. For example, the storage area for each component can accommodate 50 pieces of each component, and the staging area for each component can accommodate 4 pieces of each component. The lengths and widths of the actual areas of the subarea *i* defined in Table 1 are presented in Table 2. The aspect ratios are within the ranges defined in Table 1 and the requirements of the orientation of the subareas are satisfied. Different orientations have been considered as different actual sizes of the same subarea. In each rectangle, the aisle area has been included. To our best knowledge, no other papers in FLPs have ever dealt with aspect ratio, aisle and irregular shape at the same time for this type of port layout problem.

Different from the constraint (6) in the FLP, the port layout problem aims to generate a feasible port layout satisfying constraints (1)-(5) for an offshore wind port with the minimum total transportation cost of the components' movements between subareas, where the transportation cost is defined as a linear function of the rectilinear distance between the centres of two rectangles (Chwif et al., 1998). The closeness relationships of the subareas have been considered using a binary matrix indicating whether each component will move from one subarea to another (See Section 3.1).

From a geometric point of view, the offshore wind farm port layout problem can be considered as assigning a set of appropriate rectangular areas (e.g. loading, unloading, storage, and stage areas) to a port area of irregular shape, where each rectangle is selected from a cluster of rectangles of different sizes (as shown in Table 2). There are in total *K* clusters/subareas to consider and the set of appropriate rectangles are composed of one and exactly one rectangle from each cluster. If the *K* rectangles are chosen from the *K* clusters before the assignment process starts, the problem can be simplified to 2D irregular shape Single Bin Size Bin Packing Problem (SBSBPP) according to the typology of cutting and packing problems from Wäscher, Haußner, and Schumann (2007). We refer to our problem as **a generalized 2D irregular shape SBSBPP**. To our best knowledge, there is no such paper in the literature of

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