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A fuzzy-MADM based approach for site selection of offshore wind farm in busy waterways in China

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A B S T R A C T

The offshore wind farm has developed fast as a type of abundant, clean, renewable energy sources. The offshore wind farm located close to the shore especially in busy waterways may have significantly impact on the maritime safety. This paper proposes a fuzzy-MADM (multiple attribute decision-making) method for site selection of the offshore wind farm by comprehensively considering the feasibility of installation (i.e. cost and production) and maritime safety. The kernel of this approach is to establish a three-layer decision-making framework after identifying the influencing factors from previous works, to derive the decision matrix by integrating the influencing factor and to obtain the weights of the attributes by using the Analytic Hierarchy Process. The proposed approach is applied to a real site selection of offshore wind farm in the Eastern China Sea. The result is reasonable because it agrees with the discussion of a workshop and further analysis. Moreover, it illustrates that the maritime safety is a predominant factor for selection of offshore wind farm. Consequently, this paper provides a practical and quantitative tool for site selection of offshore wind farm.

1. Introduction

1.1. Background of offshore wind farm development

As a clean environmental energy, the offshore wind farm has developed fast in recent years worldwide (Bilgili et al., 2011; Guedes Soares et al., 2014; Sun et al., 2012; Esteban and Leary, 2012; Kaplan, 2015). Compared with the onshore wind farm, the advantages of the offshore wind farm are that there is more available space and fewer complaints about noise and visual intrusion (Sun et al., 2012). Moreover, the offshore wind farm also has the advantages of higher wind speeds, less turbulence and lower wind-shear (Bilgili et al., 2011). Upon February 2018, there are around 37 offshore wind farms with at least 200 MW nameplate capacities under operational and some others under construction (Wikipedia, 2018). Table 1 lists the top eight largest operational offshore wind farms in the world.

Although the offshore wind farm has many advantages, some disadvantages also exist. Specifically, the offshore wind turbines are expensive and difficult to install due to rough sea conditions (Sun et al., 2012), and the expensive integration into the electrical network (Bilgili et al., 2011). Therefore, many previous studies focused on the cost reduction and nameplate capacities maximization in every stage of development, manufacture, installation and operation.

Specifically, Snyder and Kaiser (2009) analysed the costs and benefits of offshore wind farm and they stressed the importance of maritime safety. Castro-Santos and Diaz-Casas (2015) proposed the location influence of the cost in lifecycle of floating offshore wind farm, and moreover, an extended work was carried out using Galicia as a case study (Castro-Santos, 2016). Studies on installation process (Barlow et al., 2015) as well as installation vessels (Paterson et al., 2017; Dalgic et al., 2015b; Sperstad et al., 2017) are also carried out to reduce the cost for offshore wind farm. Operation and maintenance are conducted for optimized planning, routing and scheduling (Dalgic et al., 2015a; Irawan et al., 2017; Rinaldi et al., 2017; Pillai et al., 2017). Moreover, the maximization of overall production is another way by optimizing the offshore wind farm layout (Chowdhury et al., 2012; González et al., 2015).

1.2. Site selection of offshore wind farm

Different from development, manufacture, installation and operation, site selection is conducted at an early-stage to determine the feasibility of wind farm by considering the environmental issues, economic feasibility, and other factors. This site selection has been widely

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Table 1
Top eight largest operational offshore wind farms in the world (Wikipedia, 2018).

Offshore wind farm	Capacity (MW)	Country	Number of turbines	Commissioned
London Array	630	UK	175	2012
Gemini Wind Farm	600	Netherland	150	2017
Gode Wind (phases 1 + 2)	582	Germany	97	2017
Gwynt y Môr	576	UK	160	2015
Race Bank	573	UK	91	2018
Greater Gabbard	504	UK	140	2012
Dudgeon	402	UK	67	2017
Veja Mate	402	Germany	67	2017

carried out both onshore (Höfer et al., 2016; Noorollahi et al., 2016; Latinopoulos and Kechagia, 2015) and offshore wind farm planning (Chaouachi et al., 2017; Fetanat and Khorasaninejad, 2015; Wu et al., 2016b).

Regarding the site selection of offshore wind farm, Chaouachi et al. (2017) used multiple attribute decision-making method (MADM) by considering security aspects, economic investment, operation costs and capacity performances. Fetanat and Khorasaninejad (2015) defined six criteria (i.e. depth and height, environmental issues, proximity to facilities, economic aspects, resource technical, and culture) together with related sub-criteria for this site selection. Wu et al. (2016b) selected the best offshore wind power station under intuitionistic fuzzy environment, and defined the wind resources, construction and maintenance conditions, supporting conditions onshore. Table 2 summarizes the method used for site selection of offshore wind farm. This table shows that the MADM method (also known as multiple criteria decision-making), which uses multiple attribute to obtain a comprehensive evaluation result, has been widely used for site selection of offshore wind farm. Moreover, in practice, it is always integrated with other methods, including Analytic Hierarchy Process (AHP), fuzzy, Decision Making Trial and Evaluation Laboratory (DEMATEL), ELimination Et Choix Traduisant la REalité (ELECTRE) and Geographic Information System (GIS).

Moreover, from previous works, the influencing factors are considered from different perspectives and are summarised in Table 3. From this table, it can be seen that few works focused on maritime safety in site selection of offshore wind farm. However, the risk analysis of offshore wind farm has attracted some attention recently (Kang et al., 2017; Shafiee et al., 2015; Abaei et al., 2017; Wu et al., 2017d). In fact, this is a significant concern of offshore wind farm especially the collision with the offshore wind farm turbine foundations (Moulas et al., 2017). Hence, the maritime safety should be considered in the stage of site selection.

Although some existing works have conducted to consider the risk of offshore wind farm when looking at the literature (BMT, 2005; Moulas et al., 2017), few studies can be found to select the best offshore wind farm in the busy waterway by addressing the problem of maritime safety. However, this is a predominant issue from the previous works (Mou et al., 2010; Yip, 2008; Zhang et al., 2016; Wu et al., 2018). Moreover, some previous works used the qualitative assessment on the criteria, which makes the model hard to be quantified and implemented. Therefore, the motivation of this paper is to propose a fuzzy-MADM approach for site selection of offshore wind farm by comprehensive considering the cost, production and safety. From this perspective, the proposed method develops a three-layer decision-making approach by treating the wind resources, natural environment, traffic environment and conditions for wind turbine as the attributes, and the associated influencing factors are identified and quantified from the previous works in order to obtain a convincing result.

The remainder of this paper is organized as follows. Section 2 develops a fuzzy-MADM approach for site selection of offshore wind farm by considering the cost, production and maritime safety. In order to verify the proposed decision-making approach, Section 3 applies this proposed approach to Eastern China Sea as a case study and the result demonstrates that this approach is practical and useful for site selection of offshore wind farm. Limitations of the proposed approach are discussed in Section 4, and the conclusions are drawn in Section 5.

2. Development of decision-making model for site selection of offshore wind farm

2.1. Establish a generic decision-making framework for offshore wind farm

The site selection of offshore wind farm is influenced by several factors, and the MADM method is widely used for such problem from Table 2. Without loss of generality, $X = \{x_1, x_2, ..., x_t\}(t \geq 2)$ is defined as a set of candidate sites for offshore wind farms. $Y = (y_1, y_2, ..., y_s)(s \geq 2)$is defined as a set of attributes. Let$A = (a_{ij})_{s\times t}$be the decision matrix, where $a_{ij}$is the attribute value. $w_i = (w_1, w_2, ..., w_s)$are the weights of the attributes, note that the weight should be greater than zero and the summation of weights should be equal to one, and this is written as $w_i \geq 0 (i = 1,2,...,s)$and $\sum_{i=1}^{s} w_i = 1$. Define $V_j$as the overall assessment on the $j$thsite of offshore wind farm, this can be written as Eq. (1).

$$V_j = \sum_{i=1}^{s} w_i a_{ij} \tag{1}$$

It can be seen that the greater value V_j is, the better the $j$thsite of offshore wind farm is. In order to obtain the overall assessment on the multiple sites of offshore wind farms, the decision-making framework is

Table 2
Overview of studies on site selection of offshore wind farm.

Study	Technique applied	Case study region	Main results
Chaouachi et al., 2017	MADM & AHP	Baltic States	The optimal wind sites reflects the characteristics of market design, regulatory aspects or renewable integrating targets
Fetanat and Khorasaninejad 2015	MADM & fuzzy DEMATEL	Iran	The best site can be selected among four alternatives and the robustness of the method is verified
Wu et al., 2016b	MCDM-ELECTRE-III	China	The site selection methodology is valid and practical
Kim et al., 2013	MCDM-GIS	South Korea	Construction costs associated with the substructure and grid connection are crucial in determining the location of the offshore wind farm
Kim et al., 2016	GIS	South Korea	The offshore wind farms can be located along a wide range of the eastern and western coasts of Jeju Island by considering energy resources and economics.
Cradden et al., 2016	MADM & GIS	Europe	The main potential for combined technologies in Europe is focused to the north and west due to strong resources and acceptable depth conditions.
Vasileiou et al., 2017	GIS & AHP	Greece	The result demonstrates the potential for deploying offshore wind and wave energy in Greece, especially in the offshore areas of Crete and in a lengthwise zone extended from North-central to central Aegean.