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A fuzzy evidential reasoning based approach for submarine power cable routing selection for offshore wind farms

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ABSTRACT

Offshore wind farms have developed fast as an environmentally friendly source of energy. The submarine power cable of the offshore wind farm, used for connecting power generation devices to onshore equipment, may have a significant impact on navigation safety and is prone to being damaged (e.g. caused by fishing or emergency anchoring by ships) when adopting unfavorable routing. This paper proposes a fuzzy evidential reasoning method for submarine power cable routing selection of the offshore wind farm by comprehensively considering the conditions for cable laying and its influence on maritime safety. The kernel of this approach is to establish a three-layer decision-making framework after fuzzification of the input variables, to derive the belief rule base, and to obtain the optimal routing from the submarine power cable candidates using evidential reasoning and index value. The proposed approach is applied to a real routing selection problem of a submarine power cable for an offshore wind farm in Zhejiang Province of China. The resulting choice corresponds to the discussions in a workshop unanimously.

1. Introduction

The offshore wind farm has developed fast worldwide as a renewable energy source for comparatively good social, environmental and climate benefits in recent years (Chancham et al., 2017; Firestone et al., 2018; Higgins and Foley, 2014; Kota et al., 2015). By the end of 2017, there was a total of 5387 MW offshore wind capacity in operation in the North and Baltic Seas (Fraunhofer, 2019a). With a large marine space with strong wind potential, the European offshore wind capacity is estimated to reach up to 150 GW by 2030 (Vieira et al., 2019; Ursavas, 2017). Compared with Denmark and UK which began to develop offshore wind power in the early 2000s (Higgins and Foley, 2014), China started later but has developed fast in the last five years especially in the southeast coastal sea (as shown in Fig. 1). Upon December 2017, the cumulative installed capacity of offshore wind farms approached 2788 MW in China and some new farms are still under construction (Zheng et al., 2018).

The submarine power cable (SPC) is an important part of the offshore wind farm which undertakes the function of power transmission (see Fig. 2), of which the routing selection is more than an economic issue since factors such as safety should be also taken into consideration. The SPC routing should be laid with caution to reduce intersections with channels in busy waterways. This is because ships that are in an emergency may take immediate anchoring (Wu et al., 2017b), which may cause damage to the cables. For different seafloor sediment and cable types, the causation factors of cable damage are quite different, of which the damage caused by human factors accounts for the most (Wang et al., 2019; Qu and Meng, 2012). Around 70 percent of cable failures are caused by fishing and shipping activities in water depths lower than 200 m (Kordahi and Shapiro, 2010). The longer the expected routing of the SPC, the higher is the probability of facing one or more faults due to human activities. Thus, optimization of SPC routing selection could facilitate a better decision process and significantly reduce the risk and costs of SPC.

Decision making for SPC routing selection mainly considers factors of cost, technical feasibility, safety and reliability, and also the sensitive regions (e.g. fishing area) which may threaten the safety of submarine cable (Fischetti and Pisinger, 2018; Schell et al., 2017; Han and Chen, 2013). According to Taormina et al. (2018), cable routing should be selected according to the bathymetry, seabed characteristics, and economic activities. Specifically, hazardous areas such as anchorages,

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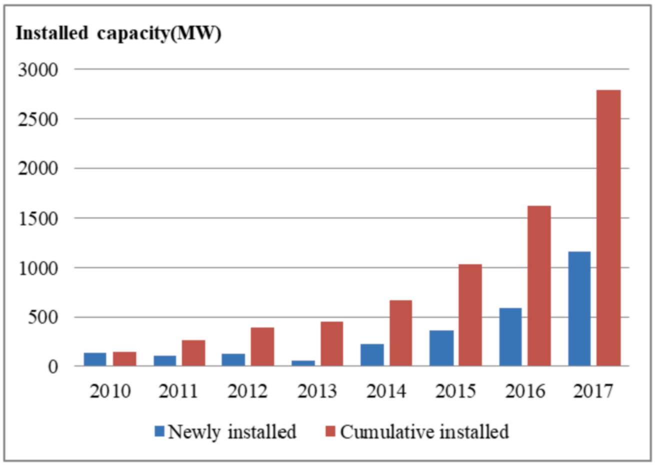

Fig. 1. Installed offshore wind capacity in China. (*Source: China Wind Energy Association*).

fishing grounds should be avoided (Worzyk, 2009). Moreover, similar to the SPC routing selection, the oil pipeline routing can also be found in the literature (Balogun et al., 2015; Dey, 2006). The existing studies for SPC routing selection are summarized as shown in Table 1.

Multi-attribute decision-making is also widely used for offshore wind farm selection (Ayodele et al., 2018; Chaouachi et al., 2017; Fetanat and Khorasaninejad, 2015; Höfer et al., 2016; Ho et al., 2018; Kim et al., 2013, 2016, 2018; Wu et al., 2018a; Zhang et al., 2018). The criteria including wind resources, technical security, environmental, economic, and social factors are often considered for wind farm selection. Specifically, Chaouachi et al. (2017) proposed an AHP method for the multi-criteria evaluation of offshore wind sites by considering the security of electricity supply and energy efficiency. Fetanat and Khorasaninejad (2015) proposed a hybrid multi-criteria decision-making tool for offshore wind site selection from water depth, environmental, technical resources and economic aspects. Ho et al. (2018) developed a comprehensive set of criteria including aspects of economy, society, environment, and security for the selection of offshore wind farm sites. Höfer et al. (2016) provided a MCDM method by considering techno-economic, social-political, and environmental criteria to

Table 1
Overview of studies on SPC routing.

Study	Topic	Technique applied	Case study region	Main results
Balogun et al. (2015)	Oil pipeline routing	Fuzzy logic-based approximate reasoning, multi-criteria decision making (MCDM)	East Malaysia	A three-layer hierarchy framework of oil pipeline routing is established. Environmental criteria have the highest influence, engineering and economic criteria rank second and third, respectively.
Dey (2006)	Oil pipeline routing	Analytic hierarchy process(AHP), multi-attribute decision-making (MADM)	India	Pipeline length, operability and maintainability are considered as sub-factors of technical factors.
Sherwood et al. (2016)	SPC routing	Field survey and multi-criteria	Bass strait	The routing for the cable is selected from pre-construction geophysical surveys. The chosen alignment has good benefits in the aspect of environmental value area and sediment.
Schell et al. (2017)	SPC routing	Multivariate adaptive regression splines model	Vancouver island	The cumulative length and water depth are important for the cost of SPC routing.
Fischetti and Pisinger, 2018	SPC routing	Mixed-integer linear programming approach	Denmark and UK	Constraints such as cable crossing, presence of obstacles in the site (e.g. nature reserve, existing cables) should be considered.

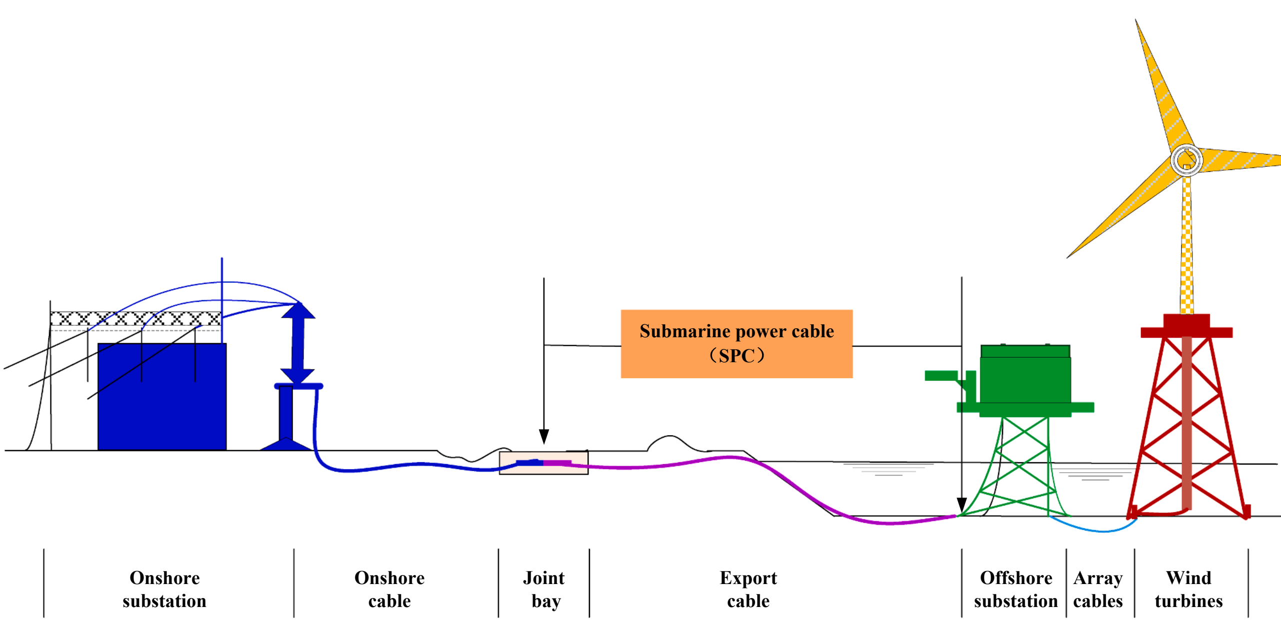

Fig. 2. Components of the offshore wind farm.

evaluate the suitability of the offshore wind farm candidates. Kim et al. (2018) provided guidance for offshore wind farm development in the South Korea southwest coast by taking criteria of economic feasibility and social-environment conflict into account. Wu et al. (2018a) proposed a fuzzy-MADM method for site selection of offshore wind farm by comprehensively considering the feasibility and maritime safety, and divided the influencing factors into four attributes, i.e. wind resource, natural environment, traffic environment, conditions for wind turbine.

Fuzzy logic is widely used for integrating these criteria to deal with uncertainties caused by the scarcity of data. Fuzzy logic, fuzzy decision trees, fuzzy AHP and picture fuzzy set (PFSs) (Fetanat and Khorasaninejad, 2015; Khakzad et al., 2017; Xue et al., 2019; Yang et al., 2009; Zhang et al., 2018; Zhou et al., 2018b; Wu et al., 2019) have been developed to achieve reasonable decisions. Fuzzy approaches can effectively describe both the qualitative and quantitative factors by using fuzzy sets. However, this approach may lose some useful information because it uses the traditional *IF-THEN* rules to describe the relationship between input variables and output variables (Yang et al., 2009). Specifically, the traditional *IF-THEN* rules describe the output with a membership degree of 100%. In practice, this is unrealistic because uncertainty may exist and a belief degree, which can precisely describe the output variables, could be much more appropriate for SPC routing selection. To address this problem, the evidential reasoning (ER), which has been widely used to deal with such uncertainty (Wu et al., 2017a, 2018b; Zhou et al., 2018a), is introduced in this paper. Moreover, this method can also cope with incomplete information, which is also common in SPC routing selection (Dymova and Sevastjanov, 2014; Liu et al., 2011; Zhang et al., 2016). The comparison between the proposed fuzzy ER and the existing fuzzy approaches is summarized and shown in Table 2. Generally, the fuzzy reasoning and ER are two different categories in terms of their inference process. The first category is human knowledge-based in the form of traditional fuzzy *IF-THEN* rules (Yang et al., 2009). The second category is to capture the nonlinear relationship between different rules and synthesize all the outputs to generate the final conclusion (Chen et al., 2018; Liu et al., 2004; Zhang et al., 2016; Zhou et al., 2018a).

Therefore, the motivation of this paper is to propose a fuzzy ER based method for SPC routing selection of offshore wind farm by comprehensively considering the cable reliability, maritime safety, and environmental protection. From this perspective, a three-layer decision-making approach by treating the routing condition, navigational environment, cable reliability, and special zones as four attributes are developed. In order to obtain a convincing result, some influencing factors related to are identified and quantified from previous studies.

The remainder of this paper is organized as follows. Section 2 develops a fuzzy ER model for SPC routing selection of offshore wind farms by considering the costs, environment and maritime safety. Section 3 applies the proposed methods to ZheNeng offshore wind farm as a case study and the results show the practicability and feasibility of this approach for SPC routing selection of the offshore wind farm. The conclusions are drawn and limitations of the proposed approach are discussed in Section 4.

Table 2
Comparison between proposed fuzzy ER and existing fuzzy approach.

Difference	Proposed fuzzy ER	Fuzzy logic	ER
Description of input variables	Utilizing membership function combined with belief degree	Utilizing the membership function	Utilizing belief degree
Description of output variables	Utilizing belief degree	Utilizing 100% certainty	Utilizing belief degree
Incomplete information	Consideration of incomplete information both in description and synthesis process	Ignorance of incomplete information in the synthesis process	Consideration of incomplete information both in description and synthesis process
Relationship of input and output variables	Using extended *IF-THEN* rules	Using traditional *IF-THEN* rules	Using extended *IF-THEN* rules

2. Development of a decision-making model for SPC routing selection

2.1. Establish a generic decision-making framework

The SPC routing selection of offshore wind farms is a common decision-making issue affected by multiple factors. Without loss of generality, $X = \{x_1, x_2, ..., x_t\} (t \geq 2)$ is defined as a set of candidate SPC routings for an offshore wind farm. $Y = \{y_1, y_2, ..., y_s\} (s \geq 2)$ is defined as a set of attributes. Define N_t as the overall assessment on the tth cable routing of the offshore wind farm.

Note that the larger the value N_t is, the better the tth routing of the cable is. In order to derive a comprehensive assessment of the multi-attribute SPC routings of offshore wind farms, the decision-making framework is established in the following three steps and graphically illustrated as shown in Fig. 3.

First, a three-layer decision-making framework is established after identifying the attributes and influencing factors, moreover, the input and output variables are fuzzified.

Second, the ER based method is introduced for the reasoning process, and the extended *IF-THEN* rules are used to construct the belief rule base.

Third, utility values are assigned to the corresponding linguistic variables and the index value is used for final decision making, henceforth the best SPC routing of the offshore wind farm can be selected.

2.2. Identify influencing factors to establish the hierarchical structure

The influencing factors of the SPC routing should be identified from previous studies or expert experience in multiple attributes decision making (Firestone et al., 2018; Ho et al., 2018; Höfer et al., 2016; Kim et al., 2013, 2018). In terms of the costs of SPC (Schell et al., 2017; Taormina et al., 2018), routing length should be considered as the key factor to assess the routing conditions of an offshore wind farm. Water depth is a distinguishing factor for cable routing selection, which will have an impact on the laying of the cable (Taormina et al., 2018) and finally influence the cost of installation. Maritime safety is the key issue for an offshore wind farm in the busy waterways. As there are many ships navigating, anchoring or fishing in the nearby channels, the routing of the SPC will have an impact on ship navigation and operation especially when the ship is not under control and an immediate anchoring could be taken (Wu et al., 2018a, 2018b). The seafloor sediment, seawater corrosion, the distance from existing cables are factors to describe the reliability of the cable routing, and these factors will influence the construction and maintenance of the cable (Woo et al., 2015). In addition, special zones (i.e. natural reverse and fishery) should be kept far from the cable routing for environmental protection. The explanation of these factors is summarized and listed in Table 3.

To facilitate the decision-making process, the categorization of the influencing factors is introduced. Four attributes, which are routing condition (***RC***), navigational environment (***NE***), cable reliability (***CR***) and special zones (***SZ***), are defined as the parent criteria of the influencing factors. Thus, the hierarchical decision-making framework for SPC routing selection of offshore wind farms can be established as shown in Fig. 4.

2.3. Fuzzy ER based approach in SPC routing selection

The widely used fuzzy approach (Balmat et al., 2009; Celik and Akyuz, 2018; Soner et al., 2017; Zhang et al., 2016) cannot precisely

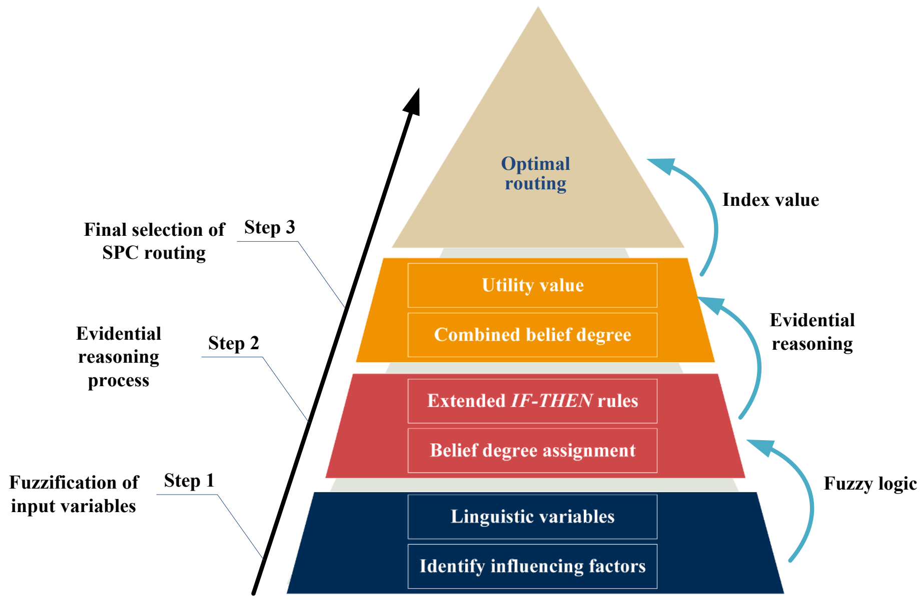

Fig. 3. A generic decision-making framework for SPC routing selection.

Table 3
Influencing factors and explanations for SPC routing selection.

Influencing factors	Explanation
Cable length(km)	Influence the costs of SPC
Water depth(m)	Influence the cable laying of SPC
Channel crossover(times)	SPC should reduce crossovers with channels
Distance from fairway(nm)	To avoid damage to SPC by ships in channels
Distance from anchorage(nm)	To avoid damage to SPC by ships in anchorage
Distance from existing cable (nm)	Influence the installation and maintenance of SPC
Seafloor sediment	Influence the installation and maintenance of SPC
Seawater corrosion	Influence the reliability and maintenance of SPC
Marine nature reserve	SPC is forbidden to be installed in this area
Distance from fishery(nm)	To avoid damage to SPC by fishing ships

describe the output, specifically in the fuzzy reasoning process, thus ER method is introduced for inference in the SPC routing selection. The fuzzy ER-based method can be graphically described as shown in Fig. 5.

Input: Influencing factors using linguistic variables or numerical values.

Output: The index value of each candidate SPC routings to derive the final decision.

Step 1: Fuzzification of the influencing factors. Qualitative influencing factors are identified by linguistic variables, while quantitative influencing factors described using numerical values are fuzzified by linguistic variables.
Step 2: Introduce the ER based approach to derive the belief rule base using the *IF-THEN* rules.
Step 3: Apply the transformation technique to link the influencing factors directly into decision variables, which is specifically explained in Sec. 2.6.
Step 4: Calculate the activation weight of each reasoning rule using the equation $\theta_k = \dfrac{\prod_{n=1}^{5} \alpha_{nJ_n}^k}{\sum_{k=1}^{125}\left(\prod_{n=1}^{5} \alpha_{nJ_n}^k\right)}$ $(k = 1, 2, \ldots, j)$. After derivation of the

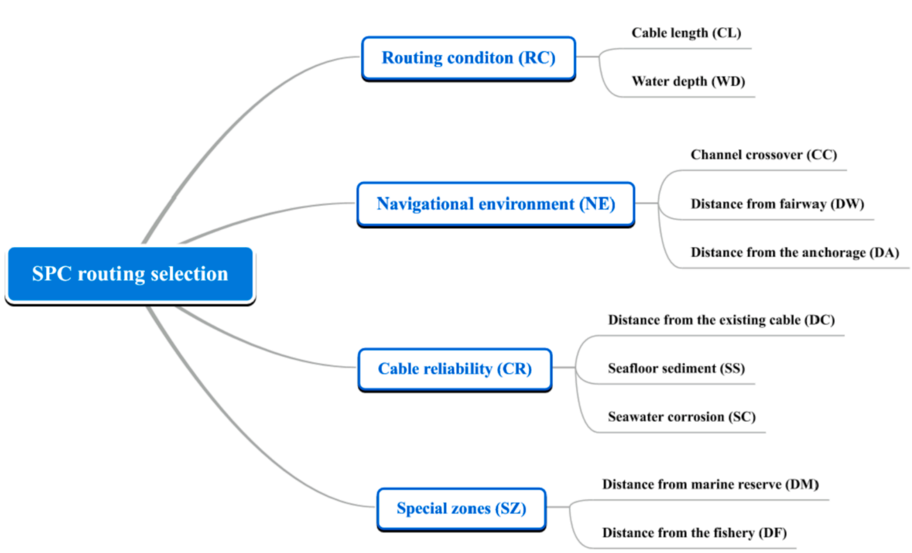

Fig. 4. A hierarchical decision-making framework for SPC routing selection.

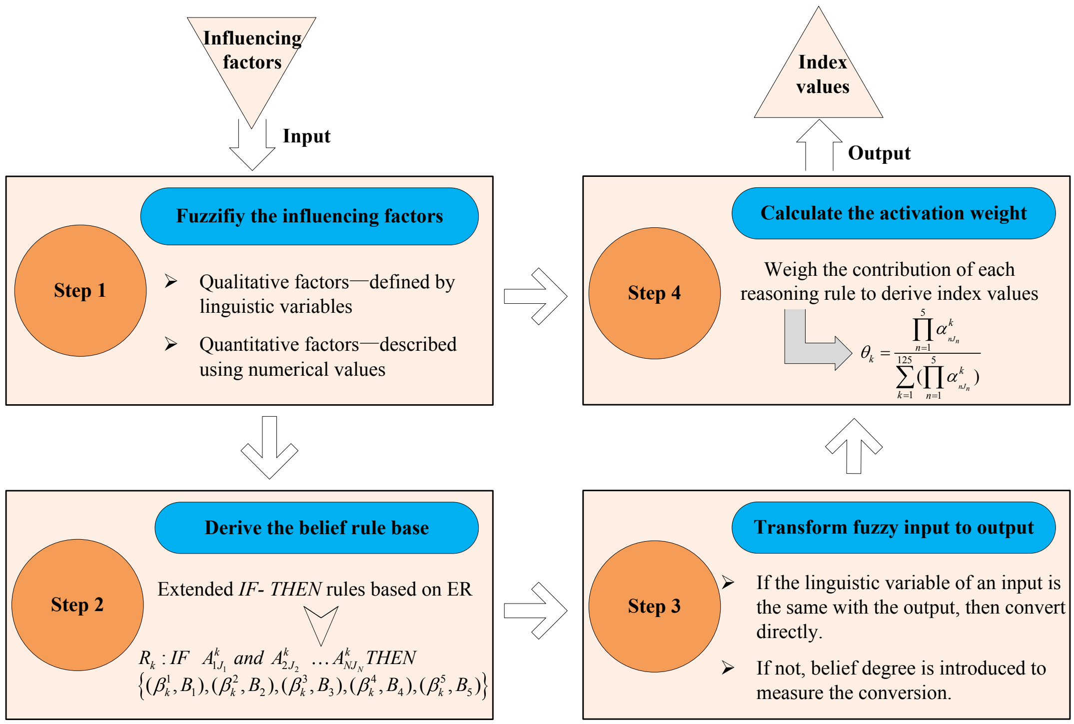

Fig. 5. Fuzzy ER process for SPC routing selection.

activation weight for each rule, the influencing factors can be integrated to derive the index values.

2.4. Fuzzification of the input and output variables

In order to facilitate the decision-making process, the input and output variables should be fuzzified to organize information. For the input variables, quantitative influencing factors and qualitative influencing factors are fuzzified separately with different methods. Expert judgment and membership functions are two methods widely used in fuzzy logic (Yang et al., 2009; Zhang et al., 2016). The former method is based on the subjective judgments of multiple experts. Hence, the qualitative influencing factors, which are seafloor sediment, seawater corrosion and marine nature reserve, are defined by fuzzy linguistic variables. On the other hand, the triangle membership function, which is commonly used in the previous studies (Coşgun et al., 2014; Wu et al., 2018a), is introduced to fuzzify the quantitative influencing factors. Five linguistic variables, which are "Very bad", "Bad", "Moderate", "Good" and "Very good", are introduced in this paper. The criteria for fuzzification of the input variables are derived on the basis of the existing SPC conditions and related rules and regulations. The fuzzification of these factors is described in detail as follows.

- Cable length (***CL***). From the figures of the European offshore wind farms, the currently farthest from shore is Global Tech 1, at a distance of 112 km from the German coast, while Finland has the shortest average distance to the coast, which is 4 km (Fraunhofer, 2019b). Likewise, to investigate the offshore wind farms installed in China, Dafeng H3 is the farthest from shore at a distance of 43 km (SPIC (State Power Investment Corporation), 2018), while the average distance is 13 km from the coast of China (Wikipedia, 2018). In this paper, 0.4 is assigned to the existing farthest European cable and 0.6 to farthest Chinese cable, respectively. Consequently, $112 \times 0.4 + 43 \times 0.6 = 70.6$, to facilitate calculation, 70 km is defined as "Very long" for ***CL***. Similarly, 10 km is defined as "Very short" for ***CL***. Moreover, the interval between 70 km and 10 km is divided into five grades as shown in Table 4.
- Water depth (***WD***). The water depth is a key factor to be considered in the site selection as well as the SPC routing selection of the offshore wind farms, which is highly related to the technology and foundation cost of the offshore wind farm. Greater distances from the coast generally go hand in hand with increasing water depths. In European countries, the offshore wind turbines in the German Exclusive Economic Zone (AWZ), are situated in the greatest average water depth at 29 m. Most of the projects are located in the water depths of up to 40 m (Fraunhofer, 2019b). However, regarding the technical and economic constraints, the water depth of a suitable offshore wind farm site should be less than 60 m (Chaouachi et al., 2017). In China, turbines are erected in more shallow water, ranging

Table 4
Fuzzified input variables for SPC routing selection.

Input variables	Very bad	Bad	Moderate	Good	Very good
CL(km)	Very long (50,60,70)	Long (40,50,60)	Moderate (30,40,50)	Short (20,30,40)	Very short (10, 20, 30)
WD(m)	Very deep (40,50,60)	Deep (30,40,50)	Normal (20,30,40)	Shallow (10,20,30)	Very shallow (5,10,20)
CC (times)	Great many (3,5,10)	Many (2,3,5)	Normal (1,2,3)	Less (0,1,2)	Very less (0,0,1)
DW(nm)	Very close (0,0,0.5)	Close (0,0.5,1)	Moderate (0.5,1,1.5)	Far (1,1.5,2)	Very far (1.5,2,5)
DA(nm)	Very close (0,0,0.5)	Close (0,0.5,1)	Moderate (0.5,1,1.5)	Far (1,1.5,2)	Very far (1.5,2,5)
DC(km)	Very close (0,0,0.5)	Close (0,0.5,1)	Moderate (0.5,1,1.5)	Far (1,1.5,2)	Very far (1.5,2,2.5)
SS	Very unsuitable	Unsuitable	Normal	Suitable	Very suitable
SC	Very strong	Strong	Normal	Slight	Very slight
DM	Exclusion area	Restricted area	Normal	Far	Very far
DF(nm)	Very close (0,0,0.5)	Close (0,0.5,1)	Moderate (0.5,1,1.5)	Far (1,1.5,2)	Very far (1.5,2,5)

from 5 m to 13 m (Wikipedia, 2018). Thus, the water depth of 5 m is assumed to be "Very shallow" and 60 m is treated as "Very deep" in this paper. According to the triangular membership function, [40, 50, 60] are defined as the fuzzy numbers for the linguistic variable "Very bad". Similarly, [30, 40, 50], [20, 30, 40], [10, 20, 30] and [5, 10, 20] are defined as the fuzzy numbers for the linguistic variable "Bad", "Moderate", "Good" and "Very good", respectively.

- Channel crossover (***CC***). Channel crossover is an indicator of the traffic situation which will influence both the laying and maintenance of the SPC in the channels. In the crossover area with channels and, if the ship navigating in the channel is not under control and have to take an immediate anchoring, the cable will be prone to being damaged by the anchor. Therefore, the more times of channel crossover with the SPC, the higher the risk of the SPC to be damaged, and the crossover times should be managed to be reduced in practice. If there is no channel cross over the SPC routing, it will be easy to protect the SPC and to enhance maritime safety. According to the national standard (GB/T 17502, 2009), the pre-selection of the submarine cable routing should take the shipping lines into consideration and the SPCs should cross the channel vertically if applicable. Although specific constraints for submarine cable crossing over the channel are not mentioned in the standard, fewer crossovers could be better from practical aspects. Through investigation of the world's top five largest offshore wind farms till 2018, the SPC of the London Array offshore wind farm (Wikipedia, 2019) crosses channels five times on its way to the landing point, while the SPC of the Race Bank offshore wind farm does not cross any main channel. Thus five times is defined as "Great Many" for ***CC*** and set as the median for the fuzzy numbers. Similarly, zero is set as the median for fuzzy numbers of "Very less". In most cases, the SPC of offshore wind farm cross channels three times and seldom reach up to ten times, thus 3 is set as the lower boundary and 10 is the upper boundary of the fuzzy numbers for "Great many", and [0, 0, 2] is defined as "Very less".
- Distance from the fairway and anchorage (***DW*** and ***DA***). These two factors have a similar impact on maritime safety but with a little difference. In the construction phase, the cable-laying vessel may disturb the ship navigating in the channel. Meanwhile, the ship mooring in the anchorage will increase the risk of traffic accidents during the cable laying operation period. In the maintenance phase, various emergency situations (such as ship out of control, ship stranded, ship sinking, emergency anchorage) may cause damage to the SPCs. Traditionally, the distance is defined by the inertial stopping distance, which is the distance that the ship stops by using the full astern engine. From the navigation experience, the inertial stopping distance of a 200,000 deadweight tonnages ship is around 16 times ship length (normally 250–300 m), which is approximately $16 \times 300\text{ m} = 4800\text{ m}$. Considering there will be larger sized ships navigating in the channels, 5 km is used as a very safe distance from the anchorage and channels. From the previous study, a 1-km buffer zone from the channel is applied to reduce the risk of collision (Kim et al., 2016). Thus, [0.5, 1, 1.5] are defined as the fuzzy numbers for "Moderate". When the SPC route is very close to the channel or anchorage, it is assumed to be "Very close". Thus the fuzzy numbers [0, 0, 0.5] are defined for the linguistic variable "Very bad".
- Distance from the existing cable (***DC***). Close to the existing cable will influence the installation of the SPCs. According to the national rules for submarine cable and pipeline protection in China, at least 0.5 km should be kept away from the submarine cables (MNR(Ministry of Natural Resources), 2004). Therefore, [0.5, 1, 1.5] is defined as "Moderate", and other four linguistic variables are defined similarly as shown in Table 4.
- Seafloor sediment and seawater corrosion (***SS*** and ***SC***). Prior to installation, a marine survey should be carried out to test the type and thickness of the sediment to see whether it is suitable for cable laying (Kraus and Carter, 2018). From the study of Sherwood et al. (2016), the routing of the cable should be selected carefully to avoid rocky outcrops including reefs and islands and to maximize the intersection of softer sediments. Additional, according to the provisions of GB17502-2009, the SPC routing should be kept far from the sensitive geological areas (i.e. exposed bedrock, steep cliff, groove, shallow gas, active sand waves). Moreover, the evaluation of the corrosion of the routing area should also be carried out. For these two influencing factors, five linguistic variables are introduced to fuzzify the impact on SPC safety.
- Distance from the marine reserve (***DM***). The laying of the SPCs may cause environmental pollution to the marine reserve. For marine environmental protection, the National Energy Bureau (NEB) and State Oceanic Administration (SOA) have issued laws and regulations that oceanographic project should not cause pollution to the marine reserve (NEB (National Energy Bureau), 2017). According to GB17502-2009, the SPC routing should be kept out of the marine reserves as far as possible. In some sensitive marine areas, marine engineering such as cable laying is forbidden.
- Distance from the fishery (***DF***). The SPC routings should avoid crossing the reef fisheries, trawl fishery and scallop fisheries (Sherwood et al., 2016). Human activities are leading causes of cable faults and repairs, and fishing accounts for around half according to the database of 2162 records of reported faults during 1959–2006 (see Fig. 6). Thus, a protection zone along the SPC should be used to avoid damage from the fishery. Similarly, 0.5 km is defined as "Very Close" as shown in Table 4. Taking the ***DW*** and ***DA*** as a reference, 5 km is treated as "Very far" from the fishery.

In order to make a comprehensive assessment of the SPC candidate routings, the energy company should compromise the above influencing factors. The fuzzified input variables are given in detail in Table 4.

For the output variables, which are routing condition (***RC***), navigational environment (***NE***), cable reliability (***CR***), and special zones (***SZ***), are all fuzzified by using the standard triangular fuzzy numbers with five linguistic variables shown in Fig. 7. The triangular fuzzy number is widely used in practice (Coşgun et al., 2014; Wu et al., 2018a), which is expressed as $M = (l, m, u)$, where m is the median for which the membership of M equals to 1, while l and u are the lower boundary and upper boundary, separately. If some unknown value locates outside $[l, u]$, it means that the variable never belongs to a member of M. Note that the boundary value is not the best value.

2.5. Construct a belief rule base using extended IF-THEN rules

After identifying the influencing factors and defining the corresponding linguistic variables, the fuzzy rules should be established to

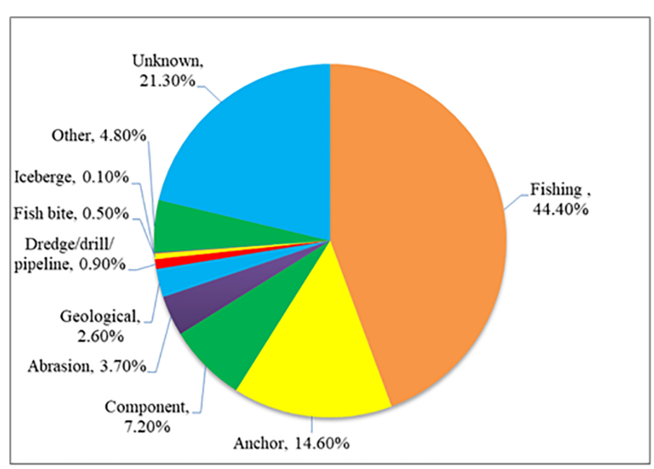

Fig. 6. The proportion of cable faults by cause, from a database of 2162 records spanning 1959–2006. (*Source: Tyco Telecommunications [US] Inc.* (Carter et al., 2009)).

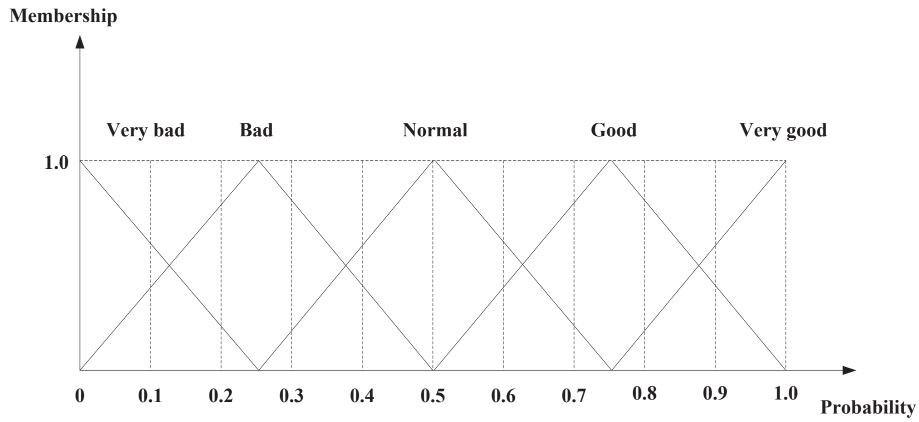

Fig. 7. Standard triangular membership function for fuzzification.

link the input variables and output variables for reasoning. The classical fuzzy rule is the *IF-THEN* rule, which is widely used in the domain of marine safety (Wu et al., 2018a; Yang et al., 2009). The influencing factors are treated as input variables and the corresponding attribute is treated as the output variable in an *IF-THEN* rule. A traditional *IF-THEN* rule can be expressed as follows (Liu et al., 2004; Yang et al., 2009):

$$R_k: \ IF \quad A_1^k \ and \ A_2^k \ and \ldots. and \ A_N^k, THEN \ D^k (k=1,2,\ldots.,L) \tag{1}$$

where A_i^k means the linguistic variables of the ith influencing factors of the corresponding attribute used in the kth rule (R_k), and D^k represent the output of the R_k rule expressed by one single linguistic variable with a 100% belief degree.

Take the attribute of ***CR*** (cable reliability) as an example, the simple *IF-THEN* reasoning rule is established as follows:

R₁: IF the ***DC*** of a routing is "Very close" *AND* the ***SS*** is "Very unsuitable" *AND* the ***SC*** is "Very strong".

THEN the ***CR*** is "Very bad".

However, this rule cannot reflect slight changes of the influencing factors and hard to describe situations with complexity and uncertainty. By introducing a belief degree (β) into the fuzzy rule system, the simple *IF-THEN* scheme is extended to assign all possible consequences with a belief degree and a more realistic and informative scheme can be established. The generic ***IF-THEN*** scheme with a belief structure is defined as follows (Yang et al., 2009):

$$R_k: \ IF \quad A_1^k \ and \ A_2^k \ and \ldots and \ A_N^k, THEN \ \left\{ (\beta_1^k, D_1), (\beta_2^k, D_2), \ldots, (\beta_M^k, D_M) \right\} \tag{2}$$

where β_j^k is the belief degree assigned to D_j, which is the consequent of output variables for the input of A_i^k and, the summation of the belief degree should satisfy $\sum_{j=1}^{M} \beta_j^k \leq 1$. The belief rule base can precisely reflect the relationships between the influencing factors and the decision attributes with probabilistic uncertainty. Hence, by using the above-mentioned rule, the extended *IF-THEN* rule with belief degree can be rewritten as follows:

R₁: IF the ***DC*** of a routing is "Very close" *AND* the ***SS*** is "Very unsuitable" *AND* the ***SC*** is "Very strong",

THEN the ***CR*** is (0.98, Very bad), (0.02, Bad), (0, Normal), (0, Good), (0, Very good).

By introducing the belief structure, the classical *IF-THEN* rule can be developed to construct the reasoning rule base using belief degree. Note that belief degrees of the output linguistic variables can be directly judged by experts or derived from matching functions. In this paper, the Max-Min operation (Zimmermann, 1991), a classical tool to define matching degree between fuzzy sets, is selected to describe the similarity between the real input fuzzy set A^r and the corresponding fuzzy linguistic variables A_{iJ_i}. Hence, the matching degree between A^r and A_{iJ_i} can be defined as follows (Liu et al., 2004):

$$\alpha_{iJ_i} = M(A^r, A_{iJ_i}) = \max\left[\min\left(\mu_{A^r}(x), \mu_{A_{iJ_i}}(x)\right)\right] \tag{3}$$

where x represents the fuzzy set of the input A^r, α_{iJ_i} express the extent to which A^r belongs to the defined linguistic variables of the ith attributes.

Therefore, the rule base for SPC routing selection can be established with the belief structure. Take the attribute ***CR*** as an example, since there are three input variables and each with five linguistic terms, 125 ($5^3 = 125$) rules could be produced to facilitate the belief reasoning process. Only some selected rules are given in the ***CR*** rule base, as shown in Table 5. The belief rule base for other attributes (i.e. ***RC***, ***NE,*** and ***SZ***) can also be constructed in the same way.

Evidential reasoning (ER) approach (Chen et al., 2018; Yang et al., 2009) is further introduced to derive the values of decision criteria, which can be implemented as follows.

Step 1: The belief degrees β_j^k should be transformed into basic probability masses m_D^k, which could be divided into two parts. The first part is caused by the relative importance of the kth rule ($\overline{m}_D^k$), and the other part is derived from the incompleteness of the belief reasoning $\beta_j^k(\tilde{m}_D^k)$. This process can be achieved by using equations as follows (Liu et al., 2004; Yang et al., 2009):

$$m_j^k = \theta_k \beta_j^k \tag{4}$$

$$m_D^k = 1 - \sum_{j=1}^{N} m_j^k = 1 - \theta_k \sum_{j=1}^{N} \beta_j^k \tag{5}$$

$$\overline{m}_D^k = 1 - \theta_k \tag{6}$$

$$\tilde{m}_D^k = \theta_k \left(1 - \sum_{j=1}^{N} \beta_j^k\right) \tag{7}$$

where m_j^k are support degrees of each R_k belongs to the output decision D, θ_k represents the relevant importance of R_k, they should satisfy $\sum_{k=1}^{N} \theta_k = 1$, and $m_D^k = \overline{m}_D^k + \tilde{m}_D^k$. Note that θ_k is a reflection of the *AND* operator between different input variables. To obtain the weight of the kth rule, the Product operator is introduced to model the *AND* connector and deal with the dependency of influencing factors for ***CR*** as follows (Liu et al., 2004):

Table 5
Belief rule base for ***CR***.

Rule No.	Input variables			Output variables(*CR*)				
	DC	*SS*	*SC*	Very bad	Bad	Moderate	Good	Very good
1	Very close	Very unsuitable	Very strong	0.98	0.02	0	0	0
…	…	…	…	…	…	…	…	…
7	Very close	Unsuitable	Strong	0	0.96	0.04	0	0
…	…	…	…	…	…	…	…	…
33	Close	Unsuitable	Normal	0	0.68	0.32	0	0
…	…	…	…	…	…	…	…	…
52	Moderate	Very unsuitable	Strong	0.33	0.33	0.34	0	0
…	…	…	…	…	…	…	…	…
90	Far	Normal	Very poor	0	0	0.20	0.60	0.20
…	…	…	…	…	…	…	…	…
111	Very far	Normal	Very poor	0	0.05	0.95	0	0
…	…	…	…	…	…	…	…	…
119	Very far	Suitable	Poor	0	0	0	0.7	0.3

$$\theta_k = \frac{\prod_{i=1}^{3} \alpha_{iJ_i}^{k}}{\sum_{l=1}^{125}\left(\prod_{i=1}^{3} \alpha_{iJ_i}^{l}\right)} (i = 1, 2, \text{or } 3; J_1, J_2, J_3, \text{and } J_4 = 1, ..., \text{or } 5) \tag{8}$$

Step 2: Generate a combined belief degree (β_j^k) of each possible D_j from all the outputs of $R_k (k = 1, 2, ..., L)$. Suppose $m_j^{I(k)}$ is the combined belief degree of D_j by integrating all the outputs of the kth rule, and $m_D^{I(k)}$ is the remaining belief degree unassigned to any D_j. Let $m_j^{I(1)} = m_j^1$ and $m_D^{I(1)} = m_D^1$. Then, the overall combined belief degree β_j of D_j can be calculated as follows (Liu et al., 2004; Yang et al., 2009):

$$\{D_j\} : m_j^{I(k+1)} = K_{I(k+1)} \times \left[m_j^{I(k)} m_j^{k+1} + m_j^{I(k)} m_D^{k+1} + m_D^{I(k)} m_j^{k+1}\right] \tag{9}$$

$$m_D^{I(k)} = \tilde{m}_D^{I(k)} + \overline{m}_D^{I(k)} \qquad k = 1, 2, ..., L - 1 \tag{10}$$

$$\{D\} : \tilde{m}_D^{I(k+1)} = K_{I(k+1)} \times \left[\tilde{m}_D^{I(k)} \tilde{m}_D^{k+1} + \tilde{m}_D^{I(k)} \overline{m}_D^{k+1} + \overline{m}_D^{I(k)} \tilde{m}_D^{k+1}\right] \tag{11}$$

$$\overline{m}_D^{I(k+1)} = K_{I(k+1)} \left[\overline{m}_D^{I(k)} \overline{m}_D^{k+1}\right] \tag{12}$$

$$K_{I(k+1)} = \left[1 - \sum_{j=1}^{N} \sum_{\substack{t=1 \\ t \neq j}}^{N} m_j^{I(k)} m_t^{k+1}\right]^{-1}, k = 1, 2, ..., L - 1 \tag{13}$$

$$\{D_j\} : \beta_j = \frac{m_j^{I(L)}}{1 - \overline{m}_D^{I(L)}} (j = 1, 2, ..., N) \tag{14}$$

$$\{D_j\} : \beta_D = \frac{\tilde{m}_D^{I(L)}}{1 - \overline{m}_D^{I(L)}} \tag{15}$$

where β_j is the normalized belief degree of D_j and β_D is the normalized remaining unassigned belief degree to any D_j.

2.6. Obtain the optimal scheme via fuzzy-link-based transformation

Multiple attributes decision-making normally contains three or more levels of criteria with different grades. For decision making, it is necessary to transform the grades of influencing factors and attributes into the grades of the decision variable. A fuzzy-link-based transformation (Yang et al., 2009) is a technique developed to convert different grades via equivalent standards. For the instance of the attribute ***RC*** (routing condition), it belongs to the upper-level criteria of SPC routing and has two lower-level sub-criteria ***CL*** and ***WD*** in the decision-making hierarchy. The top-level event "SPC routing" can be expressed using five linguistic variables, which are "Slightly preferred," "Moderately preferred," "Average," "Preferred," and "Greatly preferred." The attribute ***RC*** is described with linguistic variables of "Very bad," "Bad," "Moderate," "Good," and "Very good." The influencing factors ***CL*** and ***WD*** are assessed with the grades of linguistic variables ("Very long," "Long," "Moderate," "Short," "Very short") and ("Very deep," "Deep," "Moderate," "Shallow," "Very shallow"). Consequently, a transformation link with belief structure between different levels of criteria expressed by linguistic variables can be used to convert the input to output as shown in Fig. 8.

As demonstrated in Fig. 8, the arrows with the belief degree β indicate the relationships between linguistic variables of decision criteria on different levels. Note that the summation of the belief degree for each linguistic variable should be equal to 1. For example, the influencing factor ***CL*** with an expression of "Short" indicates that the level of the attribute ***RC*** can be "Good" with a belief degree of 0.8 and "Very good" with a belief degree of 0.2. For the best SPC routing scheme, the "Good" ***RC*** can be transformed into the SPC routing as "Good" with a belief degree of 1 and "Very good" ***RC*** can be transformed into "Very good" SPC routing with a belief degree of 1.

In order to rank the SPC routing expressed by linguistic variables, an appropriate utility value (U_v) should be assigned to each linguistic variable. In this paper, the utility value of reference as the set

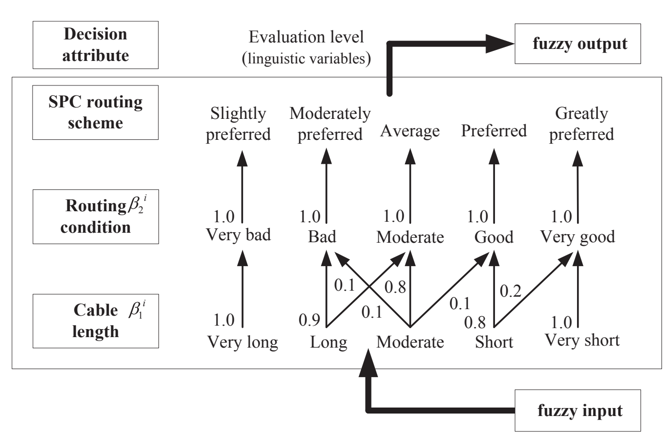

Fig. 8. Conversion of fuzzy input into the output for ***CL***.

$[0, 0.35, 0.55, 0.85, 1]$ is used for each grade (Wu et al., 2018b). The index value (N_t) for final ranking of the SPC routings can be achieved by using the following equation (Yang et al., 2009):

$$N_t = \beta_1^t \times 0 + \beta_2^t \times 0.35 + \beta_3^t \times 0.55 + \beta_4^t \times 0.85 + \beta_5^t \times 1 \tag{16}$$

where β^t is the belief degree of the SPC routing belongs to the tth grade. Note that $\sum_{t=1}^{5} \beta_j^t = 1$ for the tth SPC routing candidate. Consequently, the SPC routing selection can be conducted by using the index value. Obviously, the larger N_t means that the tth SPC routing candidate is better. Generally, the best SPC routing scheme with the largest index value will be selected.

3. Application of the proposed method to SPC routing selection

3.1. Scenario description of the SPC routing

The ZheNeng offshore wind farm (see Fig. 9) with an installed capacity of 300 MW is under planning to meet the renewable energy demand in East China. Distinguished from another offshore wind farm (i.e. Dong Hai Bridge offshore wind farm) in this area, ZhengNeng offshore wind farm intends to be developed in the port waters. In addition, there are three anchorages, namely Jinshan anchorage for ships transporting dangerous goods, Jiadian anchorage and Chenshan anchorage, scattered along the waterway for ships waiting for tide or entry. Moreover, a ten-thousand square nautical miles fishing ground is distributed close to the arranged water area which makes it complex for SPC routing selection.

As graphically displayed in Fig. 9, there are three SPC routing candidates for ZheNeng offshore wind farm, which are determined by a workshop with the attendance of stakeholders including MSA (Maritime Safety Administration), SOA (State Oceanic Administration), Traffic Planning Committee, and the energy company. Note that these three candidate routings should be proposed beforehand. This is because the SPC routing is an important part attached to the entire offshore wind farm plan, which cannot be determined independently from the offshore wind farm. In other words, the implementation of SPC routing selection without considering the conditions of the offshore wind farm will be irrational and inconvincible, and the layout of the wind farm determines the majority of the SPC routing attributes.

The basic information of the influencing factors for the three SPC routing candidates is derived as shown in Table 6. According to the location of the candidate SPC routings, the detailed information for each decision attribute is obtained from different sources. The nautical chart, as an essential tool for ship navigation, is a graphic representation of some basic data such as water depth, seabed landscape, tides and currents, navigation aids and special zones provided by International Hydrographic Organization (IHO) from hydrographic surveys. Therefore, information of the sub-factors of attributes ***CL***, ***WD***, ***CC***, ***DW***, ***DA***, ***DM***, ***DF*** and ***DC***, can be easily derived from the nautical chart. Differently, the attributes ***SS*** and ***SC***, are derived from the geological survey, including the bathymetric survey, shallow layer detection, and engineering geological investigation.

Table 6
Detailed information of influencing factors for candidate SPC routings.

Influencing factors	No.1	No.2	No.3
CL(km)	40.3	40.9	44.8
WD(m)	12	14	16
CC(times)	3	2	4
DW(nm)	0.3	1	0.3
DA (nm)	0.5	2	3
DC (km)	0.5	0.3	0.5
SS	Suitable	Suitable	Normal
SC	Very poor	Poor	Poor
DM	Far	Far	Very far
DF (nm)	2	1	1

3.2. Fuzzification of the influencing factors for SPC routing selection

By introducing the criteria for fuzzification in Table 4, the numerical values of influencing factors can be fuzzified, and the results for the three candidates are shown in Table 7. Specifically, the following

Table 7
Fuzzified influencing factors for SPC routing selection.

Influencing factors	No.1	No.2	No.3
CL (km)	(Long,0.03; Moderate, 0.97)	(Long,0.09; Moderate, 0.91)	(Long,0.48; Moderate, 0.52)
WD (m)	(Very shallow,0.80; Shallow, 0.20)	(Very shallow,0.60; Shallow, 0.40)	(Very shallow,0.40; Shallow, 0.60)
CC(times)	(Many,1.00)	(Normal,1.00)	(Many,0.50; Great many, 0.50)
DW (nm)	(Very close,0.40; Close, 0.60)	(Normal,1.00)	(Very close,0.40; Close, 0.60)
DA (nm)	(Close, 1.00)	(Very far, 1.00)	(Very far, 1.00)
DC (km)	(Far, 1.00)	(Very close,0.40; Close, 0.60)	(Close, 1.00)
SS	(Suitable, 1.00)	(Suitable, 1.00)	(Normal, 1.00)
SC	(Very poor, 1.00)	(Poor, 1.00)	(Poor, 1.00)
DM	(Far, 1.00)	(Far, 1.00)	(Very far, 1.00)
DF (nm)	(Very far, 1.00)	(Far, 1.00)	(Far, 1.00)

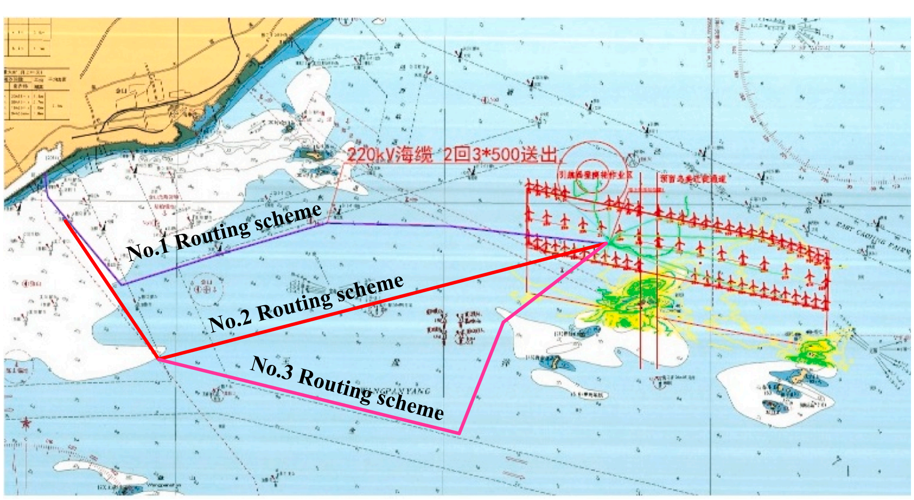

Fig. 9. Alternatives of SPC routing for ZheNeng offshore wind farm.

calculation process is described in detail by taking ***CL*** as an example. Since the ***CL*** of No.1 SPC routing is 40.3 km, the fuzzified values are shown in Table 7, and it can be interpreted as the ***CL*** of No.1 SPC belongs to "Long" with a belief degree 0.03, which is derived by using equation (40.3–40)/(50–40) = 0.03. Similarly, the ***CL*** of the No.1 SPC routing belongs to "Moderate" with a belief degree of 0.97. Hence, the ***CL*** of No.1 SPC routing can be expressed as (Long, 0.03; Moderate, 0.97). Similarly, the fuzzified values of the other influencing factors for different candidates can also be derived and shown in Table 7.

To compare the advantages and disadvantages of the three SPC routings, their performances can be graphically demonstrated in Fig. 10. There are five grades, namely G1, G2, G3, G4, and G5, representing the preference degrees of each influencing factor (IF) while G1 indicates the lowest degree with slight preference and G5 is the highest degree which is greatly preferred. In this figure, the different SPC routings are indicated by different colored shapes.

If the data point of an influencing factor falls below the line G3, it means that this influencing factor is a weak item for the overall performance. Similarly, if the data point is located in the green area, it reflects that this influencing factor has a good performance. For instance, the No.1 routing has better performance for the factors of ***WD***, ***DC***, ***SC*** and ***DF*** than the other two routings, but shows worse performances in ***CC***, ***DW***, and ***DA***. No.2 and No.3 routings have good performances in ***DA***, ***SC***, and ***DF***. Note that these three candidate routings have good performances in some factors but bad performances on some other factors. Therefore, it is necessary to make a comprehensive evaluation by accommodating all the influencing factors.

As developed in Sec. 2.5, the input variables of the three SPC routings can be defined with fuzzy values using the Max-Min operation. Note that the summation of the fuzzy values should be equal to 1. The outputs of the influencing factors from fuzzy-link-based transformation are displayed in Table 8. It can be seen that the output of each influencing factor is different from the original fuzzified result, which demonstrates that the importance degree of each influencing factor should be considered in the SPC routing selection.

3.3. Selection of the best SPC routing

After the transformation of the influencing factors, the ER method is introduced to integrate the influencing factors. The weights of the influencing factors are set the same since the significance of each influencing factor has been considered in the process of fuzzy-link-based transformation. If weights are set again here, it is duplicated and could affect the significance of the upper-level decision attributes, which may cause bias in the final SPC routing selection. The integration result of No.1 SPC routing scheme is shown in Fig. 11.

The utility values for each grade (linguistic variable) need to be defined. In this paper, they are defined as: "Slightly preferred" is 0, "Moderately preferred" is 0.35, "Average" is 0.55, "Preferred" is 0.85, "Greatly preferred" is 1.0, which is the same with Wu et al. (2018b). As introduced in Sec. 2.6, the index value N_t can be obtained by multiplying the belief degree of each grade with this defined utility value (see Eq. (16)), thus the final ranking result for the three candidate SPC routings can be derived as shown in Fig. 12.

From the comparative results of the three candidate SPC routings, No.2 SPC routing is the best, and No.1 is the worst one. The reason is that the No.2 routing has the best navigational environment (***NE***) and conditions for channel crossover (***CC***) among all candidates. Moreover, it has better performance in the attributes of ***CR*** and ***SZ***. Specifically, the No.2 SPC crosses over channel two times, while No.1 and No.3 routing cross over channels three and four times, respectively. Moreover, both No.1 and No.3 routings have a segment alongside the fairway which is more prone to being damaged by ships in an emergency. In practice, the No.2 SPC routing has the minimal interaction with ship navigation and the lowest probability to be damaged by human activities, which also suggests a reduction of the maintenance cost of SPC during the operation period.

Although No.1 candidate routing has good performance in ***WD***, ***DC***, ***SC***, and ***DF***, it is the worst scheme according to the comprehensive assessment because of the worst performance in the attributes of ***DW*** and ***DA***. In other words, this candidate routing has significant impacts on the fairway and anchorage, which may consequently cause damage to the SPC.

The final selection demonstrates that the decision being made from

Table 8
The output of the influencing factors after fuzzy-link based transformation.

Influencing factors	No.1	No.2	No.3
CL(km)	(0, 0.097, 0.779, 0.124, 0)	(0, 0.091, 0.737, 0.172, 0)	(0, 0.052, 0.464, 0.484, 0)
WD(m)	(0.280, 0.640, 0.080, 0, 0)	(0.460, 0.480, 0.060, 0, 0)	(0.640, 0.320, 0.040, 0, 0)
CC(times)	(0, 0, 0, 1, 0)	(0, 0.150, 0.700, 0.150, 0)	(0, 0, 0, 0.480, 0.520)
DW(nm)	(0, 0, 0, 0.48, 0.52)	(0, 0.150, 0.700, 0.150, 0)	(0, 0, 0, 0.480, 0.520)
DA(nm)	(0, 0, 0, 1, 0)	(1, 0, 0, 0, 0)	(1, 0, 0, 0, 0)
DC(km)	(0, 0, 0, 1, 0)	(0, 0, 0, 0.600, 0.400)	(0, 0, 0, 1, 0)
SS	(0, 0.800, 0.200, 0, 0)	(0, 0.800, 0.200, 0, 0)	(0, 0.150, 0.700, 0.150, 0)
SC	(1, 0, 0, 0, 0)	(0, 0.800, 0.200, 0, 0)	(0, 0.800, 0.200, 0, 0)
DM	(0, 0.700, 0.300, 0, 0)	(0, 0.700, 0.300, 0, 0)	(1, 0, 0, 0, 0)
DF (nm)	(1, 0, 0, 0, 0)	(0, 1, 0, 0, 0)	(0, 1, 0, 0, 0)

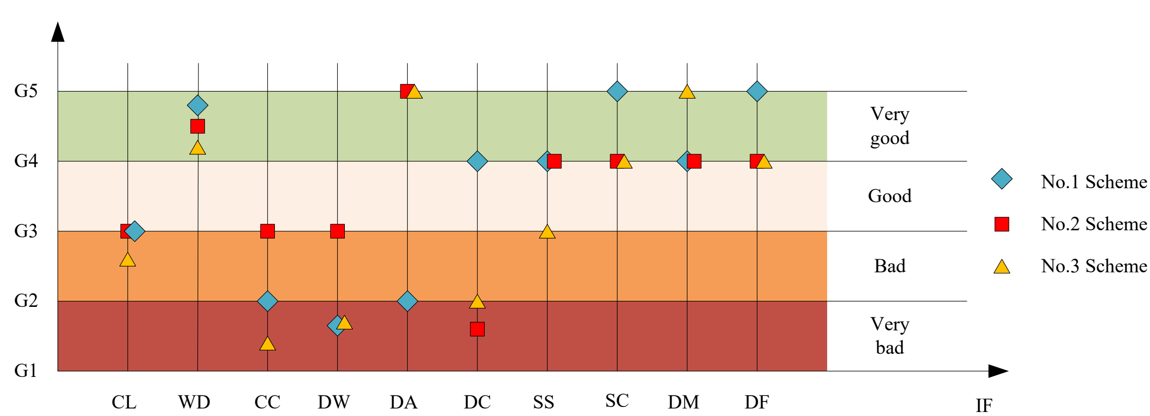

Fig. 10. Features distribution of the three candidate SPC routing schemes.

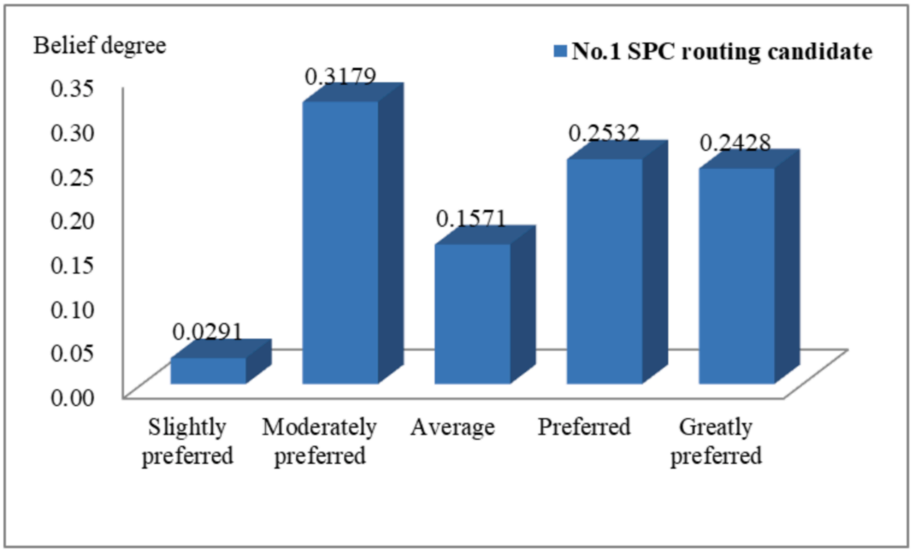

Fig. 11. The evaluation result of the No.1 candidate SPC routing.

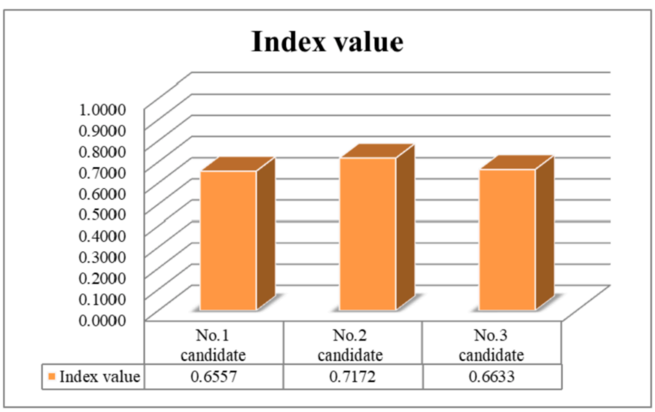

Fig. 12. Comparative results of the candidate SPC routings.

the proposed method is identical with the result discussed in the workshop, which shows that the proposed model is beneficial for SPC routing selection of the offshore wind farm. In fact, the SPC routing with minimal interaction with ship navigation is selected. It is beneficial for both installation and operation for the SPC, which could consequently enhance the safety of the SPC and reduce the operation and maintenance costs.

4. Concluding remarks

The main contribution of this paper is to propose a fuzzy evidential reasoning based method for SPC routing selection. When using the fuzzy logic-based method for selection of the SPC routings, it is hard to precisely describe the output variables using the traditional *IF-THEN* rules. Therefore, this paper introduces the belief degree to construct the extended *IF-THEN* rules for inference. From the results of the SPC routing selection, the proposed method can well address the above-mentioned problem and be applied to actual case studies in the field. The paper describes the application of the methods and techniques to ZheNeng offshore wind farm in the East Chinese Sea.

Despite the above contributions and findings, this study has some limitations. Firstly, the fuzzy criteria for input variables are derived from existing experience and studies of SPC. When it will be applied to other cases, more sources of data should be used to define the fuzzy criteria. Secondly, the influencing factors and attributes used in this paper are suitable for the East China Sea. When the proposed method will be applied to other territorial waters, the influencing factors and decision attributes should be adjusted according to the specific characteristics. Thirdly, this study focuses more on objective attributes and concerns little on social issues. Social and environmental impact on the SPC routing selection should be taken into consideration in the future.

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