A novel risk assessment approach for strait/canal security evaluation along the 21st Century Maritime Silk Road

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Abstract: The 21st Century Maritime Silk Road (MSR) designed by China is of great importance to maritime transportation, economic development, and environmental protection. However, the straits/canals along the MSR have been struggling with pirate attacks, terrorism, and accidents which pose challenges for the security of MSR. There is a strong need for further investigation in strait/canal security evaluation. However, the traditional risk modelling approach used in risk assessment indicates challenges due to its incapability of dealing with incomplete data, uncertainties, and subjective judgment. Thus, we propose a novel strait/canal security assessment framework to evaluate the security of the strait/canal along the MSR on the basis of a fuzzy evidential reasoning approach. The subjective risk analysis information collection and processing process from multiple experts can be embedded in the framework in a systematic way to provide maritime stakeholders to evaluate maritime security along the MSR. The results provide decision makers with useful insights and standard tools on enhancing strait/canal security, effective routes planning as well as operational efficiency.

Keywords: maritime security; risk assessment; Maritime Silk Road; MSR; fuzzy evidential reasoning; quantitative analysis.

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1 Introduction

The 21st Century Maritime Silk Road (MSR), initiated by China in 2013, plays an important role in transportation security, international trade, and economic cooperation, which involves 65 countries jointly account for 30% of the world economy (China International Trade Institute, 2015). It is designed with two routes, one starting from coastal China, passing through the South China Sea and the Indian Ocean to reach Europe, and the other also from coastal China, along the South China Sea flowing to the South Pacific (Jiang et al., 2018). It aims to strengthen cooperation and exchange in the economics, politics, culture, international trade, and shipping sectors. The MSR not only provides opportunities for the safety development of key nodes shipping, but also challenges for the maritime industry to reform and develop and meet the growing demands. With the initiative of this action plan, the demand for maritime transportation will increase consequently increasing the need for jointly constructing a secure, efficient, and smooth maritime transport network (Jia, 2017).

At the same time, the MSR is vulnerable to various pirate attacks, terrorism, and accidents due to its long transportation routes, a larger number of coastal countries, and critical social-political-economic functions (Wan et al., 2018). Consequently, the security of straits/canals has become crucial as they are the key nodes of the MSR and shoulder the significant responsibilities for maritime transportation (Yang et al., 2009). Once being affected by such attacks, straits/canals tend to be disruptive and inoperative thus disrupting global commerce, breaking down shipping routes, and may even cause human casualties, economic loss, and political impact (Yang et al., 2014). As a result, straits/canals security needs to be of great attention (Ghiasy et al., 2018; Li and Xue, 2015; Lam et al., 2018). Due to the cultural difference of the straits/canals along the MSR, they have different characteristics and backgrounds. Therefore, this paper proposed a novel security assessment framework that can provide a generic standard for risk analysis of straits/canals along the MSR, which will facilitate the coordination of global security resources to achieve a safer and more rational maritime transportation network.

The straits/canals are selected along the MSR account for their geo-strategic and geo-economic values, which lie in the economic and political consequences generated by their disruption, congestion, and take over by hostile forces (Lu and Gao, 2015; Popescu, 2016).In this regard, the straits/canals including Malacca Strait, Strait of Hormuz, Bab el-Mandeb Strait, Suez Canal, Strait of Bosporus and Dardanelles, Makassar Strait, and Sunda Strait are selected as the key nodes of the MSR (Lu and Gao, 2015; Li and Xue, 2015; Popescu, 2016).

In the post-9/11 era, various security measures such as initiatives, rules, and regulations have been taken by countries, organisations, and authorities to protect straits/canals along the MSR. For instance, the Malacca Strait Patrol (MSP) formed by Malacca Strait Sea Patrol (MSSP), the 'Eyes-in-the-Sky' (EiS) with Air Patrols, and the Intelligence Exchange Group (IEG) is a concrete co-operative actions adopted by Malaysia, Indonesia, Singapore, and Thailand to ensure the security of the Malacca Strait. The MSP has had great success in combating piracy and armed robbery, which can be seen through the decision made by Lloyd's Joint War Risk Committee to abandon Malacca Strait as a 'war-risk area' in 2006 and the decline in the number of piracy and armed robbery, after the implementation of the MSP. As shown in the report from IMO, the number of piracy and armed robbery in Malacca Strait dropped from 60 in 2004 to 17 and 22 in 2005 and 2006, respectively (IMO, 2019).

Different straits/canals along the MSR have diverse geography, economics, and political environment thus diversified security of straits/canals. For example, according to the US Energy Information Administration data, the most congested maritime strait is the Strait of Hormuz account for the frequent crude oil transportation from the Persian Gulf to the global demanders, followed by Malacca Strait (US EIA, 2019). Most ships that start or end in China pass through it due to its natural geographical advantages in transportation. However, the narrow waterways, intricate coastlines, and numerous high-value oil tankers have turned Malacca Strait into a 'pirate colony' (Yan et al., 2017). At the same time, the Bab el-Mandeb Strait is a narrow neck of water located between Djibouti and Yemen that separates the Red Sea from the Indian Ocean. Once closed or disrupted due to civil war or other security issues, oil tankers from the Persian Gulf and East Asia could not pass through the Suez Canal reach the western markets, forcing them to bypass the Cape of Good Hope, which would increase shipping cost and time (US EIA, 2019). As for the Suez Canal, it is one of the busiest shipping lanes which is considered to be the shortest link between Europe and the Indian Ocean due to its unique geographic location (US EIA, 2019). But its security issues are not encouraging because of its unique geographical position, political events, as well as the limitations of ships.

However, it is a challenging work to assess strait/canal security due to

1. the incomplete and ambiguous data associated with strait/canal security (Lu and Gao, 2015)
2. the various data formations of the security indicators (Yang and Qu, 2016)
3. the treatment of uncertainties (John et al., 2014).

These challenges are magnified when incorporating experts' judgement in a systemic manner. Strait/canal operation systems are sometimes presented to the public as a 'black box' due to their significant importance to countries and high-level uncertainty. Therefore, the application of conventional risk assessment approaches such event tree (ET), fault tree (FT), and failure mode and effects analysis (FMEA) (John et al., 2014) indicates two main disadvantages:

1. the lack of ability to process highly uncertain data associated with strait/canal security
2. the lack of capability of aggregating diverse formats of data in a systematic manner.

Hence, a novel quantitative risk assessment approach is needed by embedding fuzzy set theory (FST) (Zadeh, 1975) and evidential reasoning (ER) (Wang et al., 1995) approach to assess the security of straits/canals along the MSR. To be more specific, the FST is adopted to present the influencing factors using linguistic terms provided by the expert's knowledge. Then the ER (Yang, 2001) approach is applied to assess security due to its capability of aggregating various data formations and the advantage of avoiding the loss of important information in the aggregation procedure. The fuzzy *IF-THEN* rules (Yang et al., 2009; Wu et al., 2020) based on ER is used to derive the belief rule base. The rules can flexibility handle multi-level distributions and allow experts to provide ambiguous evaluation information (Wang et al., 1995). Thus, the advantages and disadvantages of fuzzy logic and ER can be shown in Table 1. Since the straits/canals along the MSR are involved many risk factors which including both qualitative and quantitative factors under uncertainties, fuzzy ER approach applied in this paper has shown its superiority in dealing with the diversity and uncertainty of various formats of information and effectively tackling linguistic evaluations for risk analysis in particular.

Table 1 Advantages and disadvantages of fuzzy logic and ER

	Advantages	*Disadvantages*
Fuzzy logic	Capable of representing vague data provided by human knowledge under uncertainties	Just a preliminary assessment method unable to conduct security evaluations
ER	Show the superiority of avoiding the loss of useful information in the inference process; high efficiency in fusing various formats of data; suitable for modelling complex systems	Need a rating as input of the ER model, usually used together with other uncertainty methods

The rest of the study is organised as follows. Section 2 reviews the relevant literature on strait/canal security evaluation. A novel framework for strait/canal security assessment is proposed incorporating the fuzzy set theory and ER approach in Section 3. Section 4 describes an application of the proposed framework by using the key nodes along the MSR as a case study, and Section 5 concludes the paper.

2 Literature review

Although a number of studies on maritime transportation security have been done in the past decade, those focus on strait/canal security have remained in its infancy. Previous maritime risks researches focused more on the disruption of seaport (Alyami et al., 2019; Cao and Lam, 2019; John et al., 2014; Yang et al., 2014; Yeo et al., 2013), security of ports (Stavrou et al., 2018), shipping risk analysis (Wang and Yang, 2018; Zhang et al., 2018; Baksh et al., 2018), and security in maritime supply chains (Wan et al., 2019a) and global trade (Wan et al., 2019b; Zhao and Chen, 2014; Liu et al., 2018). Chen et al. (2018) identified the port/shipping development along the MSR. The future trend of port and ocean shipping is expected based on the experience of Chinese ports, shipping and logistics development in the context of the MSR. Ghiasy et al. (2018) presented an analysis of the security of the 21st Century MSR, which incorporated the considerations on how the MSR might affect the interests of the European Union and the response to the MSR. Jin et al. (2019) proposed a piracy risk prediction and prevention approach to estimate the likelihood of pirate attacks by using the case study of Malacca Strait, South China Sea, and other high-risk straits/canals. By an integrated approach of negative input-output variable-based data envelopment analysis (DEA) model and technique for order preference by similarity to an ideal solution (TOPSIS), Lu and Gao (2015) analysed the security and safety control of the key straits/canals along the MSR and ranked the efficiency of security and security control among them. The aforementioned studies indicate that the security of key nodes along the MSR is attracting much attention from different perspectives.

In this study, the FST and ER approach are incorporated to conduct a risk assessment of straits/canals along the MSR. ER approach shows a powerful ability in evaluations in a synthesis manner. It has been widely used in risk areas, including Alyami et al. (2019), Cao and Lam (2019), Jiang et al. (2019), Yang (2001), Yang et al. (2009) and Yang et al. (2014). ER approach, together with other approaches such as fuzzy logic or/and BNs, has shown superiorities in handling incomplete data and uncertain subjective information, especially in linguistic assessment for risk analysis. Mokhtari et al. (2012) proposed a decision support framework that incorporated the FST and ER approach. FST was employed to represent and assess the associated risk variables within the ports using belief structures. Thereafter, an ER approach was used to aggregate the information in a systematic manner. John et al. (2014) proposed an advanced risk assessment approach incorporated the analytical hierarchy process (AHP), an ER approach, FST, and expected utility to facilitate the treatment of uncertainties. The methodology had shown its superiorities in addressing the system's risks by a flexible tool. Jiang et al. (2019) carried out a fuzzy ER method to facilitate multiple attribute decision analysis (MADA). The method allowed the establishment of decision support framework and fuzzification of the input variables and then derived the belief rule base to obtain the optimal selection.

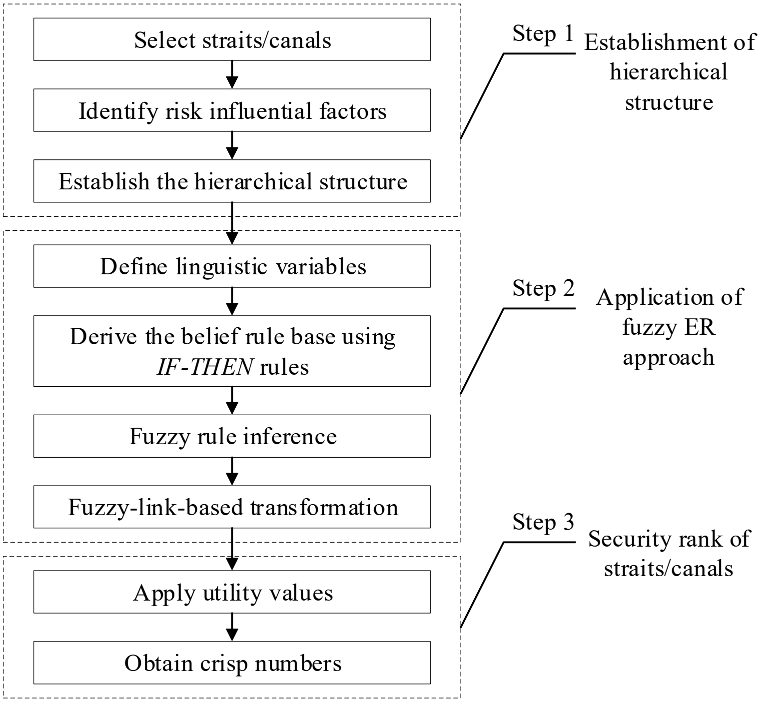
The aforementioned studies have provided a remarkable platform for further research in key nodes risk assessment against security influential factors. However, there are still limited studies focused on the security issues that affect key straits/canals along the MSR. There is an urgent need to fulfil a research gap in both academic and industrial fields.

3 The novel strait/canal security assessment framework

The generic security assessment framework shown in Figure 1 is introduced in the following three steps to assess the security level associated with straits/canals.

The first step is to establish a three-layer straits/canals assessment hierarchy. In this step, the risk influential factors and their hierarchical structures are identified. The fuzzy belief rule base is built using *IF-THEN* rules and the fuzzy ER approach is applied to synthesise the input information in the second step. Finally, the utility values are assigned to obtain crisp numbers associated with each strait/canal, henceforth the security rank of the selected straits/canals can provide insight reference to decision makers.

Figure 1 A generic security assessment framework



3.1 Establish the hierarchical structure (step 1)

The hierarchical structure of straits/canals security assessment plays an important role in the procedure of security evaluation. It discloses a better understanding of the evaluation that facilitates the stakeholders to make decisions. The influential factors of the straits/canals security can be identified from literature reviews (Ghiasy et al., 2018; Jin et al., 2019; Li and Xue, 2015; Lu and Gao, 2015; Popescu, 2016), expert experience, investigation reports, official website, and critical information present in Section 1 and Section 2. Furthermore, it is difficult to identify all the influential factors in the security evaluation process due to its complexity. Therefore, only these factors that are of significant importance to straits/canals security are considered in this paper.

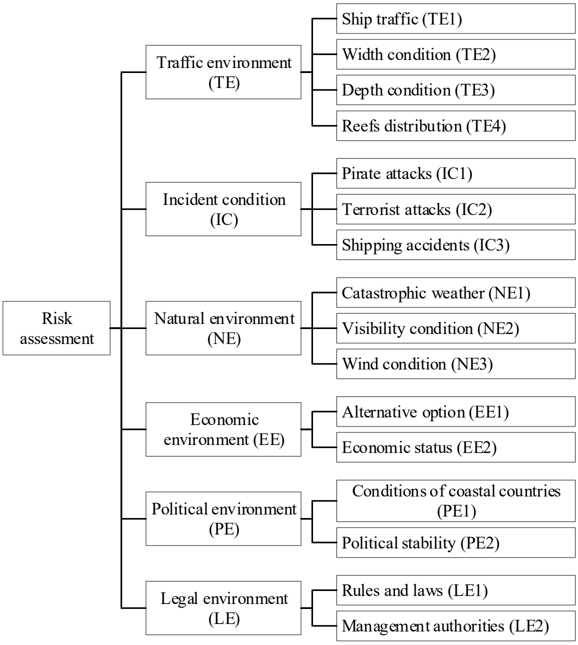
Both intrinsic and extrinsic influential factors can affect the security of straits/canals. In terms of the intrinsic factors (Lu and Gao, 2015), the basic characteristics of straits/canals such as width, depth, and reef distribution can be considered as the most important factors in evaluations. When it comes to extrinsic factors, various incidents including piracy, terrorism, and shipping accidents occurred in straits/canals is a distinguishing factor for security assessment, which will have an impact on the security level of straits/canals (Jin et al., 2019). The natural environment is also a considerable issue for straits/canals security for its prosperity in shipping. The economic, political, law and management (Li et al., 2017) are also influential factors to represent the reliability of the straits/canals, and these factors will influence the normal navigation of the straits/canals. The detail description of these factors is illustrated and listed in Table 2.

Table 2 Influential factors and descriptions for the security of strait/canal

Influential factors	*Description*	*Literature sources*
Ship traffic	The flow of ships passing through the strait/canal	Jiang et al. (2020), Zhang et al. (2016) and Mokhtari et al. (2012)
Width condition	The condition of the width of the strait/canal that influence ship traffic	Jiang and Lu (2020a) and Gong and Lu (2018)
Depth condition	The condition of the depth of the strait/canal that influences ship traffic	Jiang and Lu (2020a) and Gong and Lu (2018)
Reefs distribution	Influence the traffic environment of the strait/canal	Gong and Lu (2018)
Pirate attacks	Influence maritime security of the strait/canal	Jin et al. (2019) and John et al. (2014)
Terrorist attacks	Influence maritime security of the strait/canal	Jiang and Lu (2020a, 2020b)
Shipping accidents	Influence reliability operation of the strait/canal	John et al. (2014),
Catastrophic weather	Earthquake, typhoon, tsunami, hurricane, flooding	Wang and Yang (2018), John et al. (2014) and Mokhtari et al. (2012)
Visibility condition	Influence the navigation environment of the strait/canal	Jiang and Lu (2020a) and Wang and Yang (2018)
Wind condition	Influence the navigation environment of the strait/canal	Wang and Yang (2018)
Alternative option	Once disruption occurred, the alternative options of ships	Gong and Lu (2018) and Lam et al. (2018)
Economic status	The economic importance to coastal countries	Mokhtari et al. (2012) and Lam et al. (2018) and Jiang et al. (2018)
Conditions of coastal countries	Influence the political environment of the strait/canal	Gong and Lu (2018), Yan et al. (2017) and Lam et al. (2018)
Political stability	Political stability in coastal countries of the strait/canal	Gong and Lu (2018) and Lam et al. (2018)
Rules and laws	The condition of rules and laws related to the strait/canal	Gong and Lu (2018) and Mokhtari et al. (2012)
Management authorities	The management condition of the strait/canal	Jiang and Lu (2020a, 2020b), Zhang et al. (2016) and Yang et al. (2014)

To facilitate the security assessment procedure, four comprehensive indicators are identified as the upper indicators of the influential factors which are traffic environment (TE), incident occurrence (IO), natural environment (NE), economic environment (EE), political environment (PE) and legal environment (LE). Therefore, the hierarchical structure framework for security assessment can be established as shown in Figure 2.

Figure 2 A hierarchical structure framework for security assessment



3.2 Fuzzy ER approach in security assessment (step 2)

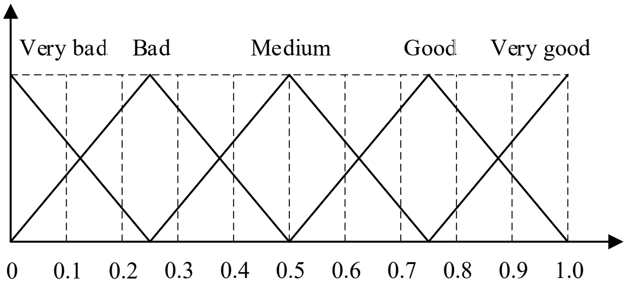
3.2.1 Definition of the fuzzy input and output variables

Since the six comprehensive factors (Figure 2) have been identified to assess the security level of the straits/canals on a subjective basis, the expert judgment using linguistic terms is more appropriate due to its flexibility and superiority in handling uncertainties. It has been widely used for real system modelling in many fields, such as disease diagnosis (Arji et al., 2019), multi-attribute decision making (MADM) (Jiang et al., 2019), maritime engineering (Wu et al., 2019a, 2019b), renewable energy (Wang et al., 2020), and risk assessment (Alyami et al., 2019; Baksh et al., 2018; John et al., 2014). The definition process includes two steps. The first step is to determine the granularities of linguistic terms for each input and output variable. The selection of fuzzy membership function types is the second step.

In respect to decide granularities for linguistic terms, the previous literature discloses that the granularity from four to seven is always used to display influential factors in risk analysis (Bowles and Peláez, 1995). Generally speaking, too few variables will limit the expression of risks by analysts, while too many variables will lead to a complicated analysis process thus increasing assessment cost. Based on the description of influential factors and previous studies (Jiang et al., 2019; Mokhtari et al., 2012; Yang et al., 2014; John et al., 2014), the linguistic terms have been described as ‘very bad’, ‘bad’, ‘medium’, ‘good’ and ‘very good’. To be more specific, the linguistic term ‘very good’ associated with the risk indicator represents that 75–100% of the selected node can be normally operated after the disturbance. A ‘good’ node associated with the risk indicator represents that the probability of providing sufficient operational function after the disturbance reaches 50–100%. Similarly, the linguistic term 'Medium' associated with the risk indicator represents that 25–75% of the selected node can be operated normally after the disturbance. The probabilities of 'bad' and 'very bad' are 0–50% and 0–25%, respectively.

Regarding selecting the types of fuzzy membership functions, it is quite difficult to construct it that fits the situation perfectly due to a lack of information. Yang et al. (2009) provided some simple straight-line membership functions to represent risk factors in security assessment that could suit different specific situations. Thus, the straight-line membership functions are used in this paper as shown in Figure 3 due to its simplicity and wide applications in risk assessment (Wang, 1997).

Figure 3 Membership function for influential factors



3.2.2 *Construct a fuzzy belief rule base*

A fuzzy rule should be constructed to build a correlation between the input and output variables after identifying the influential factors associated with linguistic terms. A fuzzy *IF-THEN* rule with belief degrees, which is widely used in risk analysis (Alyami et al., 2019; Cao and Lam, 2019; Yang et al., 2009), is preferred as it shows its superiority in dealing with uncertainties. A fuzzy *IF-THEN* rule with belief degrees can be shown as equation (1) (Yang et al., 2009):

$$\begin{aligned} &R_k : IF\ A_1^k \text{ and } A_2^k \text{ and} \ldots A_i^k \ldots \text{and } A_M^k, \\ &THEN \left\{\left(\beta_1^k, D_1\right), \left(\beta_2^k, D_2\right), \ldots, \left(\beta_j^k, D_j\right), \ldots, \left(\beta_N^k, D_N\right)\right\} \end{aligned} \tag{1}$$

R_k	the k^{th} rule, $\forall k \in \{1, \ldots, L\}$
L	the total number of the rules in the rule base
A_i^k	the linguistic variables of the i^{th} influential factors used in R_k, $\forall i \in \{1, \ldots, M\}$
M	the total number of input variables
β_j^k	the belief degree assigned to D_j, $\sum_{j=1}^{N} \beta_j^k \leq 1$, $\forall j \in \{1, \ldots, N\}$
D_j	the j^{th} consequent of output variables
N	the total number of belief degrees.

For example, a fuzzy *IF-THEN* rule with belief degrees can be established as follows:

- R$_1$: *IF* the IC1 is 'very good', AND the IC2 is 'very good', AND the IC3 is 'very good' *THEN* the IC is (0, very bad), (0, bad), (0, medium), (0.05, good), (0.95, very good).

The fuzzy rules with belief degrees are used as a premise to discretise the input variables into distributed representation. According to equation (1), the general input form associated with the antecedent attribute in the k^{th} rule is shown as follows:

$$\left(A_1^*, \varepsilon_1\right) AND \left(A_2^*, \varepsilon_2\right) AND \left(A_3^*, \varepsilon_3\right) \tag{2}$$

where ε_i represents the degree of belief corresponding to the A_i^* (i = 1, 2, 3) assigned by analysts, which describes the uncertainty of input variables. In this paper, the max-min operation matching function (Zimmermann, 1991), as shown in equation (3), is chosen to express the similarity between fuzzy sets (Liu et al., 2004).

$$\alpha_{ij} = M\left(A_i^*, A_{ij}\right) = \max\left[\min\left(A_i^*(x), A_{ij}(x)\right)\right] \tag{3}$$

where α_{ij} represents the degree to which A_i^* belongs to the linguistic variable A_{ij} with $\alpha_{ij} \geq 0$ and $\sum_{j=1}^{J_i} \alpha_{ij} \leq 1$; A_{ij} describes the j^{th} linguistic variable of the i^{th} attribute.

Therefore, the fuzzy rule base can be established with belief structures busing equations (1)–(3). For instance, the attribute TE has four input variables and each with five linguistic variables, thus lead to 625 (5^4 = 625) rules to facilitate belief reasoning procedure as shown in Table 3. The fuzzy rule base for the rest attributes in this paper is constructed in a similar way.

Table 3 The established fuzzy belief rule base for TE

Rule no.	*Input variables*				*Output variables (TE)*				
	TE1	*TE2*	*TE3*	*TE4*	*Very bad*	*Bad*	*Medium*	*Good*	*Very good*
1	Very good	Very good	Very good	Very good	0	0	0	0.05	0.95
2	Very good	Very good	Very good	Good	0	0	0.1	0.2	0.7
3	Very good	Very good	Very good	Medium	0	0.05	0.15	0.6	0.2
…	…	…	…	…	…	…	…	…	…
312	Good	Very bad	Medium	Very good	0.1	0.2	0.4	0.3	0
313	Good	Very bad	Medium	Medium	0.15	0.2	0.4	0.25	0
314	Good	Very bad	Medium	Bad	0.2	0.25	0.4	0.15	0
…	…	…	…	…	…	…	…	…	…
623	Very bad	Very bad	Very bad	Medium	0.6	0.3	0.1	0	0
624	Very bad	Very bad	Very bad	Bad	0.8	0.15	0.05	0	0
625	Very bad	Very bad	Very bad	Very bad	0.95	0.05	0	0	0

3.2.3 Fuzzy rule inference using evidential reasoning approach

ER approach is further applied to synthesise rules and derive the conclusion after obtaining the fuzzy rules with belief degrees represented in the rule expression matrix. The combination process can be achieved in the following two steps.

Step 1 Transform the belief degrees β_j^k into basic probability mass by using the following equations (Yang et al., 2009):

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

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

$$\bar{m}_D^k = 1 - \omega_k \tag{6}$$

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

$$m_D^k = \bar{m}_D^k + \tilde{m}_D^k \tag{8}$$

$$\sum_{k=1}^{L} \omega_k = 1 \tag{9}$$

m_j^k	support degrees to which each R_k associates with output D
ω_k	the relevant importance of R_k
m_D^k	assigned probability mass to D, which is unsigned to output D_j
$\bar{m}_D^k$	assigned probability mass caused by the relevant importance of R_k
$\tilde{m}_D^k$	assigned probability mass caused by the incompleteness of β_j^k.

Note that ω_k reveals the AND connecter between antecedents. Take the attribute TE for example, the activation weight ω_k can be generated as follows (Liu et al., 2004; Yang et al., 2009):

$$\omega_k = \frac{\prod_{i=1}^{4} \alpha_{ij}^k}{\sum_{l=1}^{625} \left(\prod_{i=1}^{3} \alpha_{ij}^l\right)} \qquad \forall i \in \{1, 2, 3\}; \forall j \in \{1, \dots, J_i\} \tag{10}$$

Step 2 Synthesise all the R_k to generate a fused belief degree for each consequence D_j in D. Let $m_j^{I(k)}$ be the fused belief degree of D_j by combining all the kth rule, and $m_D^{I(k)}$ be the rest belief degree assigned to D, which is unsigned to any D_j. Let $m_j^{I(1)} = m_j^{(1)}$, $m_D^{I(1)} = m_D^{(1)}$. Thus the overall fused belief degree β_j of D_j is achieved by the following equations (Liu et al., 2004; Yang et al., 2009):

$$\{D_j\} : m_j^{I(k+1)} = K^{I(k+1)} \left(m_j^{(k+1)} m_j^{I(k)} + m_D^{(k+t)} m_j^{I(k+1)} m_D^{I(k)} \right) \tag{11}$$

$$m_D^{I(k)} = \bar{m}_D^{I(k)} + \tilde{m}_D^{I(k)}, \qquad \forall k \in \{1, \dots, L\} \tag{12}$$

$$\{D\} : \bar{m}_D^{I(k+1)} = K^{I(k+1)} \left(\bar{m}_D^{(k+1)} \bar{m}_D^{I(k)} \right) \tag{13}$$

$$\{D\} : \tilde{m}_D^{I(k+1)} = K^{I(k+1)} \left(\tilde{m}_D^{(k+1)} \tilde{m}_D^{I(k)} + \bar{m}_D^{(k+1)} \tilde{m}_D^{I(k)} + \bar{m}_D^{I(k)} \tilde{m}_D^{(k+1)} \right) \tag{14}$$

$$K^{I(k+1)} = \left(1 - \sum_{j=1}^{N} \sum_{\substack{t=1 \\ t \neq j}}^{N} m_j^{I(k)} m_t^{(k+1)}\right)^{-1}, \qquad \forall k \in \{1, \ldots, L\} \tag{15}$$

$$\{D_n\} : \beta_j = m_j^{I(L)} \big/ 1 - \bar{m}_D^{I(L)}, \qquad \forall j \in \{1, \ldots, N\} \tag{16}$$

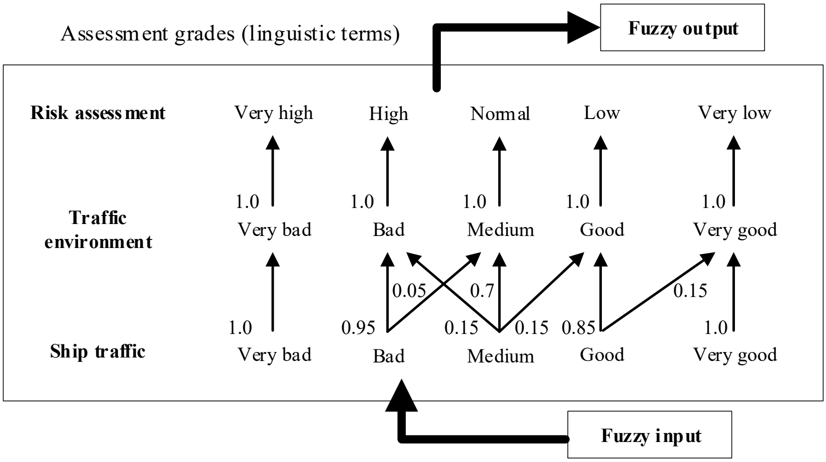
$$\{D\} : \beta_D = \tilde{m}_D^{I(L)} \big/ 1 - \bar{m}_D^{I(L)} \tag{17}$$

where β_j denotes is the combination belief degree of D_j, β_D represents the rest unsigned belief degree of any D_j, and $\sum_{j=1}^{N} \beta_j + \beta_D = 1$.

3.2.4 Apply the fuzzy-link-based transformation technique

Security assessment in this paper contains a three-layer hierarchical structure with different grades, which can be seen as a MADA problem. The defined grades from different attribute levels should transform into the same form for further evaluation. A fuzzy-link-based transformation technique, proposed by Yang et al. (2009), is therefore used to describe different grades by using equivalent standards. For example, the attribute TE has its parent level 'security assessment' and four child level 'TE1', 'TE2', 'TE3' and 'TE4' in a hierarchical structure framework. The level of 'risk assessment' can be described using five linguistic terms, which are 'very high', 'high', 'normal', 'low' and 'very low'. The attribute TE and its child influential factors can be expressed with linguistic terms of 'very bad', 'bad', 'medium', 'good' and 'very good'. Thus, a fuzzy belief link between the linguistic terms of three levels is illustrated in Figure 4 to convert the fuzzy input to output.

Figure 4 Transformation of fuzzy input to output for TE



As shown in Figure 4, the arrows with the values, assigned by experts, reveal the relationships between linguistic terms of different levels. What's more, the summation of the belief values for one linguistic term is equal to 1. For instance, the influential factor 'ship traffic' with a description of 'Medium' reveals that the attribute TE is 'medium' with a belief degree of 0.7, 'bad' of 0.15 and 'good' of 0.15. For the risk level of assessment result, the ‘very good’ TE is converted to ‘very low’ risk level with a belief degree of 1, the rest transformation can be seen clearly in Figure 4.

3.3 Obtain security rank of selected straits/canals (step 3)

The security assessment result is displayed as the formation of distributed by using the above process. It provides stakeholders a systematic view about the analysis of the straits/canals selected in this paper, from which they can realise which security level the selected strait/canal is evaluated to, and what belief degrees are assigned to the security level. However, it may not visual enough for decision makers to understand the rankings among the straits/canals. Therefore, it is necessary to introduce the expected utility value to obtain crisp security ranks to facilitate the process of decision making. Support the utility value of each assessment grade is u_p, the rank value (*RV*) of the security assessment can be calculated by using equation (18).

$$RV = \sum_{p=1}^{P} \beta_p u_p \tag{18}$$

where β_p denotes the belief degree of the risk assessment assigned to the p^{th} grade and $\sum_{p=1}^{5} \beta_p = 1$. Therefore, the rank of selected straits/canals can be determined by using the rank values. Obviously, the higher the rank value is, the more secure of the strait/canal.

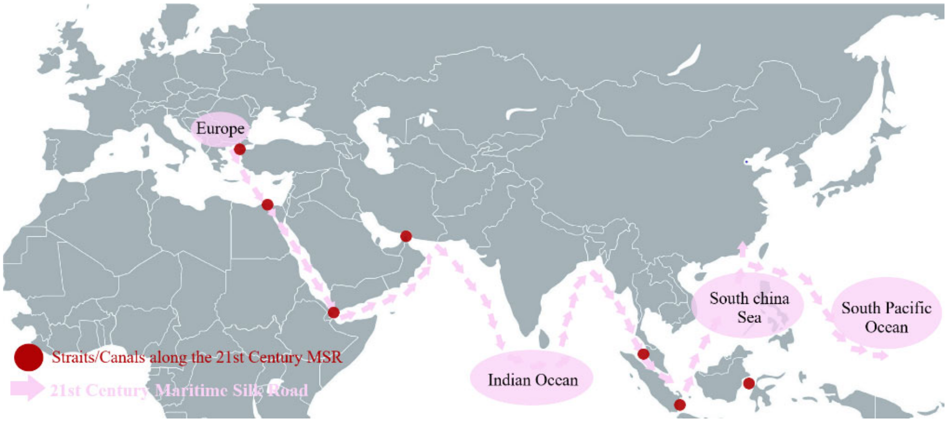
4 Case study

4.1 The application of fuzzy ER approach

Given the importance of the 21st Century Maritime Silk Road (see Figure 5), the security of the key nodes (straits/canals) along it is attracting more and more attention from various aspects (Ghiasy et al., 2018). The straits/canals along the MSR are selected along the MSR according to their values in politics and economics (Lu and Gao, 2015; Li and Xue, 2015; Popescu, 2016). As shown in Figure 5, the selected key nodes include Malacca Strait, Strait of Hormuz, Bab el-Mandeb Strait, Suez Canal, Strait of Bosporus and Dardanelles, Makassar Strait, and Sunda Strait.

After establishing the hierarchical structure framework for security assessment in Section 3.1, fuzzy ratings are constructed from ten experts by an interview from maritime security-related department and the public. The interview including the information of risk indicators associated with each strait/canal and the fuzzy ratings of them against each risk indicators. The profile of experts including four captains with more than 15 years’ working experience shipping in international routes, two senior managers in security department from shipping companies, two academic researchers engaged in 21st Century MSR safety and security. The experts are investigated to provide fuzzy ratings for linguistic terms of each influential factor based on the fuzzy membership function as shown in Figure 3. Then, the ratings from ten experts are aggregated for further calculations. The qualifications and capabilities of the experts selected for this paper were carefully evaluated during the selection process, and these experts are fully capable of effectively assessing the risk assessment issues proposed in this paper. The academic researchers have participated in and undertaken a number of practical projects addressing maritime transport security in the straits/canals and have extensive practical experience. Therefore, the influence of each expert is equal and the weight of each expert is assumed to be equal. We assume the weight of each expert is equal. The case of Malacca Strait is performed for illustration in the rest of the case study, and the other six key nodes are calculated in a similar process. Thus, the aggregated fuzzy ratings for the case of Malacca Strait are shown in Table 4. Then the max-min operation matching function proposed in Section 3.2.2 is used to define the influential factors with fuzzy values. Furthermore, the output variables are transformed from the input variables to output by using the fuzzy-link-based transformation. The fuzzy value results whose summation should be equal to 1 are displayed in Table 5. The aggregated transformed fuzzy values for the other six cases are described in the Appendix. As shown in Table 5, the output results are different from the original result shown in Table 4, which reveals that the importance weight of input variables should be taken into consideration in risk assessment.

Figure 5 Geographic coverage of the 21st Century Maritime Silk Road (see online version for colours)



Source: Background picture adapted from the Fung Business Intelligence Centre, text and picture show major MSR facts according to the Chinese official data

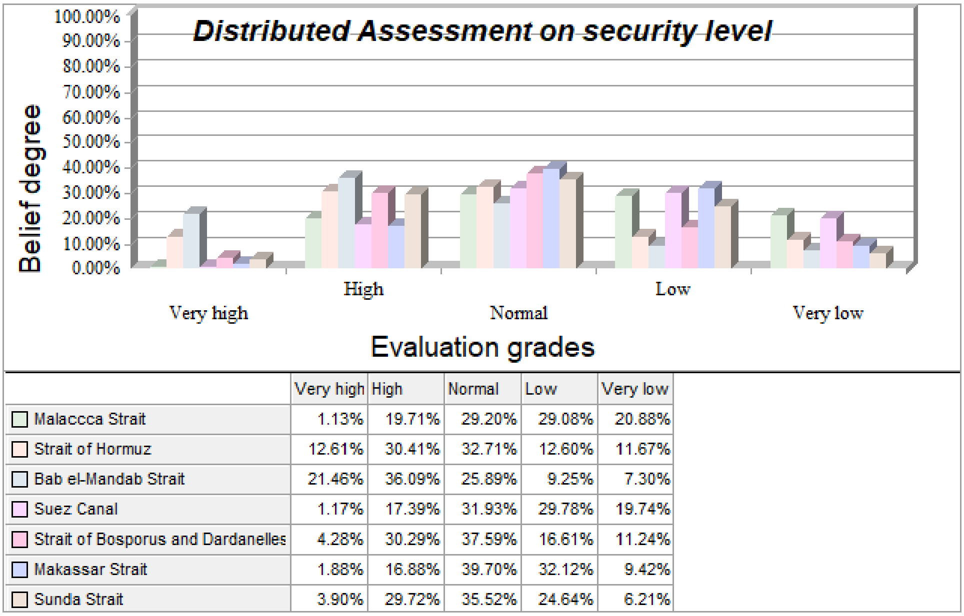
Table 4 Aggregated fuzzy ratings of influential factors: case of Malacca Strait

Influential factors	*Fuzzy ratings*	*Influential factors*	*Fuzzy ratings*
TE1	(Medium, 0.35; Good, 0.65)	NE2	(Good, 0.45; Very good, 0.55)
TE2	(Bad, 0.75; Medium,0.25)	NE3	(Good, 0.25; Very good, 0.75)
TE3	(Bad, 0.85; Medium,0.15)	EE1	(Good, 0.55; Very good, 0.45)
TE4	(Medium, 0.35; Good, 0.65)	EE2	(Good, 0.75; Very good, 0.25)
IC1	(Very bad, 0.25; Bad,0.75)	PE1	(Medium, 0.55; Good, 0.45)
IC2	(Very bad, 0.05; Bad,0.95)	PE2	(Medium, 0.65; Good, 0.35)
IC3	(Bad, 0.65; Medium,0.35)	LE1	(Medium, 0.85; Good, 0.15)
NE1	(Good, 0.35; Very good,0.65)	LE2	(Medium, 0.75; Good, 0.25)

Table 5 The output results by using the fuzzy-link-based transformation: case of Malacca Strait

Influential factors	*Transformed ratings*	*Influential factors*	*Transformed ratings*
TE1	(0, 0.053, 0.245, 0.605, 0.097)	NE2	(0, 0, 0, 0.360, 0.640)
TE2	(0, 0.750, 0.212, 0.038, 0)	NE3	(0, 0, 0, 0.200, 0.800)
TE3	(0, 0.830, 0.148, 0.022, 0)	EE1	(0, 0, 0, 0.495, 0.505)
TE4	(0, 0.052, 0.245, 0.605, 0.098)	EE2	(0, 0, 0, 0.675, 0.325)
IC1	(0.237, 0.688, 0.075, 0, 0)	PE1	(0, 0.027, 0.495, 0.388, 0.090)
IC2	(0.047, 0.858, 0.095, 0, 0)	PE2	(0, 0.032, 0.585, 0.313, 0.070)
IC3	(0, 0.602, 0.380, 0.018, 0)	LE1	(0, 0, 0.807, 0.178, 0.015)
NE1	(0, 0, 0, 0.280, 0.720)	LE2	(0, 0, 0.712, 0.263, 0.025)

Figure 6 The overall evaluation results for straits/canals by the ER approach



	Very high	High	Normal	Low	Very low
☐ Malaccca Strait	1.13%	19.71%	29.20%	29.08%	20.88%
☐ Strait of Hormuz	12.61%	30.41%	32.71%	12.60%	11.67%
☐ Bab el-Mandab Strait	21.46%	36.09%	25.89%	9.25%	7.30%
☐ Suez Canal	1.17%	17.39%	31.93%	29.78%	19.74%
☐ Strait of Bosporus and Dardanelles	4.28%	30.29%	37.59%	16.61%	11.24%
☐ Makassar Strait	1.88%	16.88%	39.70%	32.12%	9.42%
☐ Sunda Strait	3.90%	29.72%	35.52%	24.64%	6.21%

Having obtained the transformed linguistic terms with fuzzy values, the ER approach is applied to aggregate the influential factors. The activation weights ω_k are calculated by using equation (10) to construct a rule base. The overall aggregate result is shown in Figure 6. It can be seen from Figure 6, the results of Malacca Straits, (very high, 1.13%, high, 19.71%, normal, 29.20%, low, 29.08%, very low, 20.88%), represent that the risk level is assessed as very high with a belief degree of 1.13%, high with a belief degree of 19.71%, normal with a belief degree of 29.20%, low with a belief degree of 29.08%, very low with a belief degree of 20.88%. The results of other straits/canals can be described in the same way. It is not straightforward for decision makers to rank the risk levels form the distributed assessment results. It is necessary to introduce the preference information for each evaluation grade to facilitate the decision process. Utility function in Figure 7 is proposed for illustration purpose to describe the preference information. As shown in Figure 7, the utility values are defined as (0, 0.25, 0.5, 0.75, 1). The rank value (RV) can be calculated based on equation (18), thus the ranking result for risk levels of the seven straits/canals is obtained as shown in Figure 8. Suez Canal has the best score of security level, followed is Malacca Strait, Strait of Bosporus and Dardanelles, Makassar Strait, Sunda Strait, Strait of Hormuz, and Bab el-Mandeb Strait, respectively.

Figure 7 Utility function

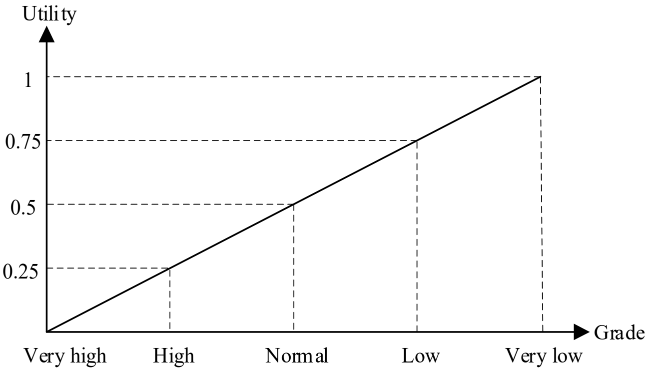
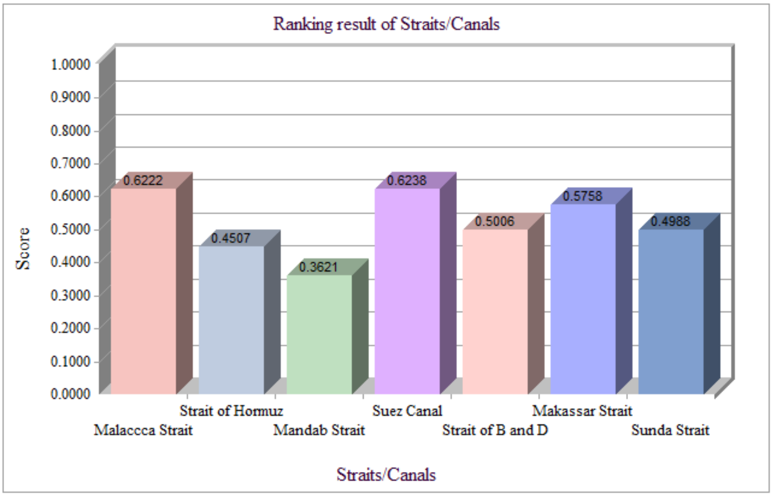


Figure 8 Ranking result of straits/canals (see online version for colours)



4.2 *Analysis and discussions*

This section presents the results and analysis of the straits/canals along the MSR. From the ranking results shown in Figure 8, the security condition of the Suez Canal is the best with a score of 0.6238, and the strait/canal with the second-highest score is the Malacca Strait, which is similar to the literature results (Lu and Wang, 2015; Gong and Lu, 2018). The main reasons for this are the existence of specialised authorities responsible for the two sea lanes and the favourable navigation conditions, including the absence of small waves and reefs. There is a small difference between the results of this paper and that of the literature (Lu and Wang, 2015). The Makassar Strait is more secure than Sunda Strait. The reason for its higher security is because the influence of the natural environment (e.g., catastrophic weather) is considered in this paper. The Sunda Strait has poor security for its poor natural environment and traffic environment (reefs distribution). Natural environment and traffic environment are sometimes important to the security of straits/canals, these factors cannot be ignored in security assessment.

The security of the Suez Canal ranks best in this paper. Suez Canal is a man-made sea-level waterway without locks that connects the Mediterranean Sea to the Indian Ocean through the Red Sea. In 2014, it was widened from 61 meters to 312 meters to speed the transit time thus increasing the capacity. In 2016, the new side-channel was officially opened by the Suez Canal Authority (SCA). Therefore, the good condition of the traffic environment is one of the reasons for the best-ranking result. Besides, the canal is owned and operated by the SCA of the Egyptian government. Given the importance of the canal in terms of economic development and political stability, measures and rules that ensure reliable transportation are greatly enhanced by the SCA. All vessels are allowed to transit through it subject to comply with Rules of Navigation, which provide security for the canal. Furthermore, the alternative routes, Cape Agulhas, Northern Sea Route, and Negev desert railroad, are available to bear the responsibility for shipping.

The Malacca Strait, which connects the Indian Ocean and the South China Sea, has also got a good score of 0.6222, only marginally lower than the Suez Canal. Since it is one of the most important and busiest shipping lanes in the world, measures to maintain security in the Malacca Strait have been taken by the three littoral states, and military assistance has been offered by other countries to jointly ensure the smooth and efficient operation. What's more, the natural environment is suitable for shipping all year round. Although, there are sometimes thunderstorms during the period of monsoon, the condition of visibility and wind is generally good except for the occasional bad weather. Then, the alternative routes such as Sunda Strait, Lombok Strait, and the pipeline of oil and gas to Myanmar are available in case of its disruption. The alternative routes will be more in the future with the rapid development of the Belt and Road (B&R).

Regarding the Strait of Hormuz, and Bab el-Mandeb Strait, the overall security condition seems not very good with the respective score of 0.4507, 0.3621 compared to the other straits/canals. The Strait of Hormuz is regarded as the most strategically important shipping lane for international trade that links the Persian Gulf with the Gulf of Oman. It is a narrow stretch of water with many islands, reefs, and shoals that may easily cause stranding, grounding and collision, especially for the large tonnage oil tanker. In addition, it was reported by the Global Integrated Shipping Information System (GISIS) that piracy and armed robbery is one of the main incidents. All the above conditions lead to a low score of the security situation. As for the Bab el-Mandeb Strait, its security performance was the worst in this paper. It acts as a strategic link for oil and natural gas shipments between the Red Sea with the Gulf of Aden and the Indian Ocean. Most exports of oil and natural gas from the Persian Gulf pass through the Bab el-Mandeb Strait and the Strait of Hormuz. Therefore, the security condition is of great importance for global energy security. The pirates based in Somalia, a chronically weak and insecure state is the main threat to the security of el-Mandeb Strait. Furthermore, submerged reefs, rough seas, and narrow lanes will also pose threats to the vessels.

5 Discussion and research implications

Notably, by applying the proposed generic framework, this study can provide maritime stakeholders and academic researchers with deeper research implications, including:

1. Managerial implications for maritime stakeholders: the rapid development of the MSR has facilitated the transformation of strait/canal security research field from individual analysis with different criteria at a single node to integrated analysis with the same framework of a group of nodes on a maritime transportation network. The generic criteria framework for straits/canals security assessment along the MSR proposed in this paper provides maritime stakeholders with an effective and powerful tool to make more rational security decisions through comparative analysis of the security of other relative straits/canals along the MSR.
2. Empirical implications for straits/canals managers: the proposed generic framework with a hierarchical structure can improve the visibility and efficiency of strait/canal security in terms of various risk factors, so that strait/canal managers can improve their security along the MSR through the experience and best practice from other relative straits/canals. In addition, it allows strait/canal managers to better understand, learn and apply the experience and practices of other straits/canals and provides them with diagnostic tools for better identification of the risk factors.
3. Comparative analysis of straits/canals: it is well worth noting that the role of each strait/canal along the MSR is crucial, as their geographical locations cover almost all the necessary routes for the movement of cargoes between Asia, Africa, and Europe. Therefore, this study established a standard framework that allows the assessment of different types of risks by assessing the security of seven major straits/canals. Decision makers can rationalise the allocation of security resources for straits/canals based on the results of the comparative analysis of the performance of selected risk factors on straits/canals, thus improving the robustness and efficiency of straits/canals. On the other hand, lessons can be also learned from the poorly performing ports against the selected risk factors. For instance, in Section 4.2, Suez Canal ranks first due to its good condition of the traffic environment, legal environment, and economic environment. This indicates that policy makers could adjust their strategies by referencing the experience and practice in terms of the best factors to improve the overall robustness of the strait/canal along the MSR.
4. A new application of fuzzy ER approach of strait/canal security evaluation along the MSR: this is a new study taking into account the superiority of the fuzzy rule base and the ER approach model using quantitative and qualitative factors to propose a common security evaluation for robustness maritime transportation and bring new thinking in security evaluation of transport node in a complex network.

6 Concluding remarks

Security analysis always needs domain experts’ judgement as risk-related data are usually incomplete. A fuzzy ER approach-based framework is proposed to incorporate subjective judgment in the process of security assessment under uncertainty. This paper shows that the novel framework is capable of presenting the input and output variables precisely by using the fuzzy *IF-THEN* rules with a structure of degrees of belief. Besides, by using the ER approach, the assessment information of seven selected straits/canals is synthesised to generate the distributed assessment result. In order to show the result in a more intuitive way, the expected utility function is used to compare and rank the selected straits/canals. More importantly, it provides a powerful risk assessment tool for key nodes security management. Also, some useful implications can be obtained from this paper which shed lights on practical situations for decision makers, authorities, and shipping companies. The proposed framework can be applied to more key nodes under different conditions in future studies.

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Appendix

The output results for the other six cases

Straits/canals	*Influential factors*	*Transformed ratings*
Strait of Hormuz	TE1	(0, 0.052, 0.245, 0.265, 0.438)
	TE2	(0, 0.322, 0.190, 0.208, 0.280)
	TE3	(0, 0.212, 0.115, 0.405, 0.268)
	TE4	(0.100, 0.735, 0.142, 0.023, 0)
	IC1	(0.522, 0.433, 0.045, 0, 0)
	IC2	(0.427, 0.433, 0.135, 0.005, 0)
	IC3	(0.190, 0.517, 0.280, 0.013, 0)
	NE1	(0, 0, 0.285, 0.215, 0.500)
	NE2	(0, 0, 0.285, 0.255, 0.460)
	NE3	(0, 0.090, 0.295, 0.255, 0.360)
	EE1	(0.090, 0.192, 0.445, 0.248, 0.025)
	EE2	(0.090, 0.197, 0.535, 0.163, 0.015)
	PE1	(0.160, 0.212, 0.455, 0.143, 0.030)
	PE2	(0.120, 0.275, 0.435, 0.140, 0.030)
	LE1	(0.180, 0.500, 0.310, 0.010, 0)
	LE2	(0.225, 0.465, 0.300, 0.010, 0)
Bab el-Mandeb Strait	TE1	(0, 0.432, 0.265, 0.265, 0.038)
	TE2	(0, 0.352, 0.330, 0.280, 0.038)
	TE3	(0, 0.242, 0.255, 0.435, 0.068)
	TE4	(0, 0.750, 0.212, 0.038, 0)
	IC1	(0.617, 0.348, 0.035, 0, 0)
	IC2	(0.665, 0.305, 0.030, 0, 0)
	IC3	(0.190, 0.602, 0.200, 0.008, 0)
	NE1	(0, 0, 0.190, 0.210, 0.600)
	NE2	(0, 0, 0.332, 0.258, 0.410)
	NE3	(0, 0.135, 0.252, 0.333, 0.280)
	EE1	(0.270, 0.402, 0.315, 0.013, 0)
	EE2	(0.180, 0.277, 0.375, 0.153, 0.015)
	PE1	(0.320, 0.355, 0.312, 0.013, 0)
	PE2	(0.120, 0.423, 0.440, 0.017, 0)
	LE1	(0.450, 0.290, 0.250, 0.010, 0)
	LE2	(0.315, 0.475, 0.205, 0.005, 0)

The output results for the other six cases (continued)

Straits/canals	*Influential factors*	*Transformed ratings*
Suez Canal	TE1	(0, 0.037, 0.175, 0.505, 0.283)
	TE2	(0, 0.512, 0.200, 0.250, 0.038)
	TE3	(0, 0.655, 0.207, 0.123, 0.015)
	TE4	(0, 0.052, 0.245, 0.605, 0.098)
	IC1	(0.190, 0.645, 0.160, 0.005, 0)
	IC2	(0.095, 0.815, 0.090, 0, 0)
	IC3	(0, 0.560, 0.420, 0.020, 0)
	NE1	(0, 0, 0, 0.200, 0.800)
	NE2	(0, 0, 0, 0.320, 0.680)
	NE3	(0, 0, 0, 0.240, 0.760)
	EE1	(0, 0, 0, 0.675, 0.325)
	EE2	(0, 0, 0, 0.720, 0.280)
	PE1	(0, 0.037, 0.675, 0.238, 0.050)
	PE2	(0, 0.027, 0.495, 0.388, 0.090)
	LE1	(0, 0, 0.902, 0.093, 0.005)
	LE2	(0, 0.080, 0.732, 0.173, 0.015)
Strait of Bosporus and Dardanelles	TE1	(0, 0.082, 0.385, 0.295, 0.238)
	TE2	(0, 0.560, 0.202, 0.208, 0.030)
	TE3	(0, 0.735, 0.142, 0.108, 0.015)
	TE4	(0, 0.227, 0.185, 0.505, 0.083)
	IC1	(0.332, 0.603, 0.065, 0, 0)
	IC2	(0.142, 0.688, 0.165, 0.005, 0)
	IC3	(0.095, 0.602, 0.290, 0.013, 0)
	NE1	(0, 0, 0.190, 0.210, 0.600)
	NE2	(0, 0, 0.095, 0.325, 0.580)
	NE3	(0, 0, 0.285, 0.255, 0.460)
	EE1	(0, 0.182, 0.445, 0.338, 0.035)
	EE2	(0, 0.192, 0.625, 0.168, 0.015)
	PE1	(0, 0.177, 0.545, 0.228, 0.050)
	PE2	(0, 0.102, 0.520, 0.308, 0.070)
	LE1	(0.180, 0.420, 0.385, 0.015, 0)
	LE2	(0.090, 0.370, 0.517, 0.023, 0)

The output results for the other six cases (continued)

Straits/canals	*Influential factors*	*Transformed ratings*
Makassar Strait	TE1	(0, 0.037, 0.175, 0.590, 0.198)
	TE2	(0, 0.067, 0.315, 0.535, 0.083)
	TE3	(0, 0.052, 0.245, 0.605, 0.098)
	TE4	(0, 0.575, 0.272, 0.138, 0.015)
	IC1	(0.332, 0.603, 0.065, 0, 0)
	IC2	(0.142, 0.773, 0.085, 0, 0)
	IC3	(0, 0.772, 0.220, 0.008, 0)
	NE1	(0, 0, 0.142, 0.688, 0.170)
	NE2	(0, 0, 0, 0.680, 0.320)
	NE3	(0, 0, 0.190, 0.290, 0.520)
	EE1	(0, 0.022, 0.405, 0.518, 0.055)
	EE2	(0, 0.032, 0.585, 0.348, 0.035)
	PE1	(0, 0.022, 0.405, 0.383, 0.190)
	PE2	(0, 0.027, 0.495, 0.308, 0.170)
	LE1	(0, 0.080, 0.875, 0.045, 0)
	LE2	(0, 0.200, 0.762, 0.038, 0)
Sunda Strait	TE1	(0, 0.132, 0.180, 0.590, 0.098)
	TE2	(0, 0.790, 0.180, 0.030, 0)
	TE3	(0, 0.670, 0.277, 0.053, 0)
	TE4	(0, 0.750, 0.212, 0.038, 0)
	IC1	(0.427, 0.518, 0.055, 0, 0)
	IC2	(0.237, 0.688, 0.075, 0, 0)
	IC3	(0.095, 0.687, 0.210, 0.008, 0)
	NE1	(0, 0, 0.190, 0.650, 0.160)
	NE2	(0, 0, 0, 0.640, 0.360)
	NE3	(0, 0, 0.190, 0.410, 0.400)
	EE1	(0, 0.022, 0.405, 0.518, 0.055)
	EE2	(0, 0.037, 0.675, 0.263, 0.025)
	PE1	(0, 0.027, 0.495, 0.388, 0.090)
	PE2	(0, 0.032, 0.585, 0.313, 0.070)
	LE1	(0.090, 0.410, 0.480, 0.020, 0)
	LE2	(0, 0.440, 0.537, 0.023, 0)