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Review

Risk assessment of maritime supply chains within the context of the Maritime Silk Road

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ABSTRACT

This work aims to apply a novel approach to assess the risks of maritime supply chains (MSCs) within the context of the Maritime Silk Road (MSR) by employing fuzzy logic and evidential reasoning. Compared to traditional risk analysis methods, the novel approach has its superiorities in dealing with incomplete and vague data, synthesizing multiple data formats, and preventing the loss of important risk information. A case of the risk factors influencing MSCs along the MSR is analysed, and the assessment results reveal that the fuel price is the most significant risk factor. Sensitive analysis is applied to validate and illustrate the rationality and practicality of the proposed approach. The findings can provide the MSR stakeholders with important insights for the safety management of MSCs along MSR.

1. Introduction

The 21st Century Maritime Silk Road (MSR), launched by China, is one of the two most essential aspects of the Belt and Road Initiative (BRI), which has promoted a large number of international maritime transportation activities. Since the promulgation of the BRI, many scholars have been studying it from different perspectives, including risks, vulnerabilities, and connectivity (Lee et al., 2018a, 2018b, 2022). The BRI which consists of the China Railway Express (CR Express) and the MSR has connected China to the rest of the world by sea. The MSR originally drawn by a Chinese institute (or government agencies) does not cover most ports in the sub-Saharan region and South America and Oceania. Recently, the scope of the original MSR has been expanded to include the major ports in the above-named regions within a 'New MSR' concept by Lee et al. (2018b).

The BRI connecting Southeast Asia, Africa, and Europe accounts for about 60% of the world's population, more than 20% of the household consumption and around 30% of the world's GDP (CITI, 2015). Due to its large coverage, a lot of economic activities have been and will be continuously carried out such as the development and/or up-gradation of ports and maritime shipping networks among more than 65 countries. As a result, global maritime supply chains (MSCs) have been increasingly developed (Thürer et al., 2020) and undertaking changes. The MSR places emphasis on seaport, railways, highway connectivity and cultural, economic, political cooperation and communication between the countries along the route. It aims to strengthen cooperation and communication priorities, including unimpeded international trade, economic globalization, infrastructure connectivity, and shipping route safety (Jiang et al., 2020). It will no doubt stimulate the sustainable development of coastal nations with trade via oceans.

With the initiative of the BRI, the developed maritime trade will result in increasing demand for international logistics, which heavily relies on the connectivity and efficiency of MSCs (Lee et al., 2020). Generally speaking, 80% of international trade is completed through maritime transportation (UNCTAD, 2019). The stability of the MSCs is related to the stable development of international trade and the economy. The safe operation of MSC plays an important part to ensure the sustainability of maritime transportation. As an important part of the international logistic system, MSCs connect different transport modes to provide shippers with seamless door-to-door services (Wan et al., 2019a). However, the rapid development of global trade and economic globalization also brings uncertainties and risks to MSCs, hence making

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it difficult despite the necessity and urgency of assessing the risks (Wan et al., 2019b). Recent literature (e.g., Jiang et al., 2021; Lee et al., 2020) reveals that the resilience and safety of MSCs should be analysed in different scenarios or backgrounds in combination with the latest development trends and strategies of the involved countries, where risk assessment of MSCs within the context of the MSR becomes necessary. This paper aims to propose a generic and standard framework that can facilitate the risk assessment of MSC, hence enabling the identification and application of risk events and their measures.

Previous studies analysing risks concerning MSCs include the disasters that occurred at MSC components (e.g., explosion of Tianjin Port), terrorist attacks and lock-out of port, etc. They arise high attention to risk assessment of MSCs. MSC risks can be described as the existence of potential risk events such as fierce market competition, fluctuating fuel prices, growing requirements from customers, and maritime accidents related to transportation that may negatively impact the connectivity of MSCs (Lam and Bai, 2016; Feng et al., 2022; Yang, 2011). In this paper, MSC risks are negatively affected by risk events and factors in the above definition. The risk factors that appear in the paper are defined as the risk events that occurred along with an MSC of the MSR. Once an MSC is affected by any form of disruption, its performance will be affected, in terms of business sustainability and transport capability among others. In addition, these effects on one transport node will negatively be passed onto other links/nodes through the MSC and generate high indirect losses. For instance, in 2002, a 10-day blockade of U.S. West Coast ports caused around $20 billion in damages (Gorman, 2015). In 2015, a major explosion occurred at the Port of Tianjin, where a series of chain explosions led to 173 deaths and hundreds of injuries. Therefore, it is important to clearly understand the risks facing MSCs and accurately evaluate and effectively manage risks associated with MSCs (Vilko and Hallikas, 2012). However, the MSC-related literature focuses more on operations (Lam, 2015; Lam and Bai, 2016; Thürer et al., 2020) and has very little research investigating MSC risks.

A careful literature review reveals that many approaches have been proposed and used to conduct risk evaluation. They can generally be classified into two categories. One is the traditional methods such as fault tree analysis (FTA) (Gascard and Abazi, 2018), failure mode effect analysis (FMEA) (Qin et al., 2020), and analytic hierarchy process (AHP) (Mangla et al., 2015). The other involves novel techniques including fuzzy logic (Wan et al., 2019a), Bayesian network (BN) (Jiang and Lu, 2020; Nguyen, 2020), Monte Carlo simulation (Gascard and Abazi, 2018), and evidential reasoning (ER) (Yang et al., 2014). However, these existing approaches in many cases will expose their inherent deficiencies when being applied individually in practical applications. For instance, it may be difficult for the traditional approaches applied individually to tackle the complexity in the risk assessment of MSCs. To address this problem, numerous hybrid approaches based on uncertainty theories have been proposed, based on such standing-along methods/theories as Dempster-Shafer (D-S) theory, fuzzy logic, and BN modelling. Among these hybrid approaches, fuzzy-ER is deemed as an effective solution to risk assessment involving subjective survey data. The ER approach is one of the multiple criteria decisions making (MCDM) methods firstly presented on the basis of the D-S evidence theory and decision theory (Yang and Singh, 1994). It is applied to modify the evidence by weights and improve the D-S theory in many applications. The ER approach combined with fuzzy logic to address its inherence shortcomings has also been well documented in a wide range of its applications (e.g., Yang et al., 2014; Wan et al., 2019a; Zhang et al., 2016). Moreover, in addition to the two risk parameters of possibility and severity that have been studied for years, there are many studies which have proposed other parameters to conduct risk assessment from multi-perspectives (Nguyen et al., 2019; Alyami et al., 2014; Wan et al., 2019b). Therefore, the study of risk evaluation of MSCs from multi perspectives under high uncertainty in data is full of research challenges which are yet well addressed and have shown no evidence of any study within the context of the MSR. Given such challenges in the method, data, and research content, it is of urgent necessity to propose a risk assessment approach of MSCs within the context of the MSR. It will also bring new theoretical contributions of 1) use of ER to develop risk models of a multiple-tire risk parameter hierarchy and extension of supply chain related risk studies from a local node level to a whole chain perspective in which the influence of risk from one node passing to another can be addressed by new variables such as risk visibility and controllability.

This paper aims to develop an advanced risk assessment model on the basis of fuzzy logic and the ER method to prioritize the risk events affecting MSCs from multi perspectives within the context of the MSR. To be specific, the risk events are identified from different perspectives. It is critical to identify the risk events, which can help understand where a risk may derive from, and then assess their risk levels so that rational countermeasures can be made to ensure the safety of MSCs. There are many works focusing on maritime safety issues from different perspectives including operational (Yang et al., 2013; Nguyen et al., 2019; Nguyen and Wang, 2018), human and organisational factors (Chauvin et al., 2013; Fan et al., 2020), and security factors (Yang et al., 2009, 2014; Lu et al., 2022). Although valuable implications have been drawn from previous studies on risk assessment, they have usually been analysed from a single perspective, which leads to their significance not being fully appreciated from a multiple perspective. Hence, it shows a research gap to fulfil with the increasing growth of maritime transportation along the MSR. Then, the risk parameters are determined through the literature review and domain experts' knowledge. These risk parameters are utilized to build a hierarchical structure for risk assessment. The fuzzy logic and ER approach are adopted to assess the risk events of MSCs of the MSR under uncertainty for the first time. A case analysis is finally applied to validate the rationality of the proposed approach. Implications in terms of risk assessment under uncertainties can be drawn from this paper which shed light both on researchers and practical users relating to safe MSR.

In this paper, fuzzy logic is applied to deal with risk data with diverse formations (Wan et al., 2019a). The ER approach is used to assess the risk of MSCs for its suitability in dealing with diverse data formations and its superiority in minimizing the loss of significant information with uncertainties (John et al., 2014). The fuzzy ER approach in the formation of IF-THEN rules with a belief structure is applied to synthesize rules for its advantages in the inference between input and conclusions (Yang et al., 2009, 2014). Then the utility functions are used to prioritize the risk factors to facilitate the decision-making process. The novelty of this manuscript can be summarized as (1) the risk events that occurred along the MSCs are, for the first time, identified from a multi-perspective including operational, managerial, infrastructural, external environmental, technical, and financial; (2) the risk parameters involved in this paper integrate the research results from a multi-perspective such as the probability, severity, visibility, uncertainty, and controllability to facilitate the modelling and understanding of risk characteristics of MSCs; (3) the proposed model-based fuzzy logic and the ER approach shows its superiority in dealing with uncertainty in risk data by using belief structures and synthesizing both incomplete and complete information properly; (4) a generic and standard framework is proposed for the risk assessment of MSCs within the context of the MSR; and (5) incorporation of new risk parameters involved in the multiple perspectives from a supply chain viewpoint brings new theoretical solution on how to use FER to model complex risks of advanced systems which are often presented in different tiers in a hierarchical structure.

The rest of this manuscript is organized as follows. Section 2 reviews the literature on the study of the definitions of risks of supply chains and the approaches used in risk assessment. In Section 3, the details of the proposed approach incorporating fuzzy logic and ER for risk assessment are illustrated. A case analysis of the risks of the MSR is conducted to validate the rationality and feasibility of the proposed approach in Section 4. Finally, Section 5 concludes the study with major contributions and future studies.

2. Literature review

2.1. The definition of MSC risks

Modern supply chains are complex networks that require a high degree of coordination of goods, information and capital to provide seamless service, which makes them vulnerable to all kinds of risks (Vilko and Hallikas, 2012). In terms of risk analysis, risk investigation has been studied to aid maritime administrations to formulate regulations for the sustainable ocean and coastal development and conservation (Pazoto et al., 2022; Nguyen et al., 2022). This type of research investigates the high-risk areas by identifying the occurrence of the incidents. Some studies tend to investigate the relationship among risk factors by using uncertainty approaches. For instance, Jiang et al. (2021) applied an ER approach and develop a novel port vulnerability assessment framework to analyse port risks from a supply chain perspective. Poo et al. (2021) used an ER approach to assess climate change risks for seaports, and the finding was used to guide rational coastal management, governance issues, and policy making in aiding adaptation planning for the sustainability of coastal nations against climate change.

In the substantial supply chain risk assessment-related literature, the risk is defined as purely negative terms which result in unimaginable adverse consequences (Harland et al., 2003). The risks could come from natural environment (e.g., catastrophic weather), accidents (e.g., piracy, collision), fierce market competition, technical failure, human factors, political instability, and cyber-attacks (Lam and Bai, 2016). Nevertheless, the literature on MSCs risk assessment is still in its infancy. Wan et al. (2019b) provided a systematic assessment of the MSCs risks related to container transportation that may lead to various kinds of hazards. Jiang et al. (2020) argued that ship accidents, navigation environment and the technical system of ships are the most important maritime risks, while Vilko and Hallikas (2012) ranked human factors, information systems, navigation conditions and fire as the top four risks of MSCs. Vilko et al. (2019) also indicated the common problems of limited visibility and control in MSCs and inadequate understanding of MSC related risk characteristics. In the above research, the risk is generally represented in a standard formula as $risk = P * S$, where P is defined as the probability of occurrence and S is the severity of consequence. The simple combination of P and S is to some extent an effective expression of maritime risks. To be more specific, some types of risks such as operational risks, which usually happen regularly, can be realised as either high or low according to its severity of consequences. However, disruptive risks are considered as low probability and high severity hazards. The current study on risk assessment of supply chains mostly focuses on two risk parameters, (i.e., probability and severity of consequence), which could result in biased information needed for decision-making, given the fact that the risk of one element in an MSC could generate a negative impact on the other elements in the upstream/downstream of the same chain. In other words, the risk of an MSC is affected by both internal and external risk levels with a transmission ability across MSC components. Hence, risk variables that can be used to model the external risk should be added in the risk expression formula.

However, there is no alignment on the definition of risk in the maritime industry at present. Many studies (e.g., John et al., 2014; Vilko and Hallikas 2012; Aven, 2012) used two categories of risk parameters (i.e., probability and severity of consequence) to quantify risks. A small number of studies (Wan et al., 2019a; Vilko et al., 2019) considered other risk parameters such as visibility when more complicated systems (e.g., MSCs) are modelled. Nguyen et al. (2019) used the concept of risk events, consequence, and uncertainty in maritime shipping. Risk visibility, defined as a result of external integration, is one of the significant parameters in the risk assessment of supply chains. Good visibility provides benefits with operational efficiency, productivity, stability and safety planning (Yu and Goh, 2014). The higher a risk's visibility, the lower the associated risk. The definition of risk controllability shares a similar characteristic to the definition of risk control, which is considered as a core step of risk management procedure where safety measures are taken to mitigate risks (Tummala and Schoenherr, 2011). It is noteworthy that the definition of risk can be interpreted from different views of points to meet the needs of various applications. The most used definitions that can well present the characteristics of risks are summarized in Table 1. There is no uniformed concept on supply chain risk definition available in the current literature, requiring new parameters to address the risk evolution from a single risk level to a network resilience perspective. Risk visibility and controllability become increasingly important due to the ambiguity caused by the involvement of multiple upstream and downstream participants in the same chain.

In this paper, the concepts of MSC risks used in the previous literature are investigated, and the likelihood of occurrence, the severity of consequence, risk visibility and controllability are for the first time, selected as the parameters to jointly present MSC risks from a supply chain/network perspective (Wan et al. 2019a, 2019b; John et al., 2014; Vilko et al., 2019).

2.2. Risk assessment approach

Traditional approaches such as FMEA are among the most widely used risk assessment methods due to their transparency and simplicity (Braglia et al., 2003). It has three basic attributes (probability of occurrence, severity of consequence, and possibility of the risk being undetected) that have been included to conduct a risk assessment (Nguyen and Wang, 2018). However, as aforementioned, the traditional FMEA method shows certain deficiencies in dealing with uncertainties, which has prompted the development of new extended FMEA approaches, by incorporating uncertainty modelling theories like ER, Grey system theory, fuzzy logic and BNs to facilitate their applications in the maritime industry (Yang and Wang, 2015), maritime port safety and security (Alyami et al., 2019; Yang et al., 2009), MSC risk (Wan et al., 2019a), and marine engineering system safety (Liu et al., 2005).

In this work, MSC risk assessment is conducted by using an advanced approach based on FER. Fuzzy logic is widely applied to handle the situations, where it is difficult to get a clear answer or information to describe risk parameters. The methods incorporating fuzzy logic are powerful to model system behaviours which are too complicated to use traditional approaches, or when addressing the uncertainties caused by the scarcity of available data and information (Wan et al., 2019a). However, fuzzy logic without the use of a rule base to represent the causal relationships between variables may result in the loss of important risk input information (Yang et al., 2009). An IF-THEN rule base is probably the most used method to deal with human knowledge systematics at present. The concept of degree of belief is employed to extend a classical rule base to handle the uncertain environment well (Yang et al., 2006). To be more specific, the classical rule base represents the variables with a membership degree of 100%. In real situations, it

Table 1
Interpretation and definition of risk.

Related risk parameters	Interpretation/description	Reference
probability and severity of consequence	It is generally defined as the probability of the occurrence of risk events and their severity consequence.	Wan et al. (2019b); John et al., (2014); Vilko and Hallikas (2012); Aven (2012)
Probability, severity of consequence, visibility, and controllability	In addition to probability and severity of consequence, risk visibility and controllability are also key elements in MSC risk management.	Vilko et al., 2019; Wan et al., (2019a)
Probability, severity of consequence, and uncertainty	Risk is defined as the combination of the risk events, their severity consequence, and uncertainty	Nguyen et al., 2019; Nguyen and Wang (2018); Aven (2010);

may be unrealistic due to the uncertainties and the degree of belief, which describes the variables completely, can improve the accuracy of risk assessment under high uncertainty in data.

The ER approach, which has been widely used in many industries to handle uncertainties (Jiang et al., 2019; Alyami et al., 2019; Cao and Lam, 2019; Mokhtari et al., 2012), is used for risk synthesize in this manuscript. Furthermore, this approach can also handle incomplete data, which usually exists in risk assessment (Liu et al., 2004). Therefore, the ER approach in combination with other uncertainty modelling techniques has presented its superiority in dealing with the variety and uncertainty of the subjective information derived from experts' experience and tackling the incompleteness, vagueness, and uncertainty in data. John et al. (2014) developed a novel approach integrating ER, fuzzy logic, and expected utility to analyse the risk of seaport operations. The proposed method provided a flexible and robust way of dealing with uncertain, vague, and incomplete data and also allow for a systematic way of synthesizing all the available information. The proposed method was validated in a sense that it can provide port stakeholders with a useful tool to improve the resilience and safety of their ports systematically. Zhang et al. (2016) introduced an advanced approach on the basis of fuzzy rules and ER to conduct the risk assessment of ship navigation. A fuzzy rule-based technique was first applied to transform quantitative data into qualitative data, and ER was then adopted to aggregate the risk information along with the hierarchical structure under uncertain environment. The procedure of information transformation and risk estimates synthesis was facilitated by Intelligent Decision System (IDS) Software. Jiang et al. (2019) presented an ER approach based on fuzzy logic for submarine power cable routing selection. The fuzzy logic in this paper was used to define the input and output variables through linguistic terms, fuzzy membership functions, and a fuzzy rule base with belief degrees. The ER algorithm and expect utility values were adopted to evaluate the routing schemes. Although the powerful ability in dealing with uncertainty in data, the use of fuzzy ER in supply chain risk assessment is scanty compared to its applications in the other sectors. More importantly. The available studies of using FER in the nearest areas (i.e. transport risk assessment) are largely based on single-tier risk index analysis (e.g., Yang and Wang, 2015) and taking into account fewer risk parameters from a network perspective (e.g., risk visibility) and addressing resilience concerns (e.g., risk controllability).

Sensitivity analysis (SA), which has been widely used in validating knowledge-based systems (John et al., 2014; Mokhtari et al., 2012; Yang et al., 2009), is introduced to validate and demonstrate the rationality and practicality of the proposed approach in this paper. There are other available techniques used for model validation such as informal validation, validation by testing, field test, and subsystem validation. They are generally applied to engineering systems that can be tested or simulated in the field and sometimes are not applicable to risk assessment models under uncertainties. The error rate, overall accuracy, precision, and recall are usually used to validate the performance of dynamic systems (Sun and Sun, 2015; Yeo et al., 2013). Compared to them, SA has been chosen in this paper for its powerful ability (Gonzalez and Dankel, 1993). Wan et al. (2019a) proposed a SA to verify the robustness and logicality of a new BN-based risk model. John et al. (2016) have undertaken a SA to conduct a model validation process and to identify the relative influence of different risk variables in a port system.

2.3. Research gaps and contributions

To address the current shortcomings for risk assessment of MSC within the context of the MSR, this study attempts to fill the gaps of previous studies by completing the following goals: (1) to decide the risk events and risk parameters related to the MSC risks within the MSR context; (2) to propose a hybrid FER approach to conduct risk evaluation under uncertainties; (3) to validate the rationality and practicality of the developed generic approach; and (4) to find the most important risk events influencing the safety of MSC along the MSR. The contributions of the study are summarized as follows with more details as compared to the relevant studies in Table 2:

(1) Present new points of view for risk assessment of MSC within the context of the MSR. This paper analyses the MSC risks from the perspective of the implementation of MSR.
(2) Development and validation of a powerful approach to assessing MSC risks under uncertainty.
(3) Better implications for maritime stakeholders. Useful implications are obtained from the analysis results which shed light on decision makings for maritime stakeholders.
(4) New risk model capable of dealing with advanced supply chain systems of complex risk variables which are first located in different tiers of a hierarchical structure and secondly aid the risk foci transformation from classical single dimensional risk analysis towards systematic network resilience evaluation.

3. Methodology

Quantitative risk assessment (QRA) approaches are applied to estimate risks in MSC operations. However, the lack of objective data is a great challenge in the shipping industry to conduct a QRA fully. Thus, it is necessary to incorporate subjective and qualitative information into risk assessment procedures, which will inevitably produce uncertainties due to the incompleteness and ambiguousness of expert information. In light of this, an ER approach on the basis of the fuzzy rules is presented to evaluate the risks along with the MSC within the context of the MSR, in which fuzzy logic is applied to handle the incompleteness, vagueness, and uncertainty of expert judgements and ER is applied to synthesize all the information. The novelty of this proposed approach lies in its good ability to capture the relationships between risk parameters and risk status (e.g., the input and output are not necessarily linear) and to fuse diverse data information in a systematic manner, thus effectively handling uncertainties in the risk assessment procedure.

The proposed approach as shown in Fig. 1 consists of four major steps. Details are described in the following sections.

3.1. Establishment of a hierarchical structure for MSC risk assessment

The likelihood of occurrence and the severity of consequence are two of the most common risk parameters in risk assessment. The decomposition of consequence can facilitate the identification of their impacts on maritime transportation. Some consequences (i.e., time delay) can be measured easily, while the others are difficult to assess, such as loss of human resources. In the recent studies of risk assessment in MSCs, Vilko et al. (2019) introduced three categories of risk consequences for MSCs, and they are time-based, finance-based and quality-based. Chang et al. (2015) also introduced three categories of risk consequences in the development of risk maps including financial loss, reputation loss, and safety and security incident-related loss. According to the previous studies and the characteristics of MSCs along the MSR, this work considers three categories of risk consequences: time delay/disruption, financial costs, and quality loss.

Time delay/disruption brings pressure on the service reliability of liner shipping. Maritime shipping sometimes can be delayed for weeks without serious consequences, while on the other occasions delay even for days can cause significant losses, which depend on the kinds of goods being shipped (Vilko and Hallikas, 2012). For instance, the time delay consequences for the goods that are sensitive to season, holidays and temperature is facing more seriousness than other goods. In addition, disruption is described as a failure in MSCs, which can lead to a time delay in maritime transportation. Hence, the time delay/disruption is considered as one of the risk parameters in this paper. Financial costs include the additional costs derived from the management and operations (e.g., additional maintenance costs after a risk event) and accident

Table 2
Incremental contribution of the paper compared to the state-of-the-art.

Items	Descriptions with the existing studies	Incremental contributions
Risk events	Previous studies have been analysed from a single perspective, such as operational (Yang et al., 2013; Nguyen et al., 2019; Nguyen and Wang, 2018), human and organisational factors (Chauvin et al., 2013; Fan et al., 2020), and security factors (Yang et al., 2009, 2014; Lu et al., 2022).	The risk events that occurred along the MSCs are identified from a multi-perspective including operational, managerial, infrastructural, external environmental, technical, and financial.
Risk parameters	The risk is generally represented in a standard formula as risk = P*S, where P is defined as the probability of occurrence and S is the severity of consequence (Wan et al., 2019b; John et al., 2014; Vilko and Hallikas 2012; Aven, 2012). A small number of studies (Wan et al., 2019a; Vilko et al., 2019) considered other risk parameters such as visibility or controllability when more complicated systems (e.g., MSCs) are modelled. Uncertainty sometimes was considered in some literature (Nguyen et al., 2019; Nguyen and Wang, 2018).	The risk parameters applied in this paper from a multi-perspective such as the probability, severity, visibility, uncertainty, and controllability have been used to facilitate the modelling and understanding of risks in MSCs.
Approach	Traditional approaches such as FMEA are among the most widely used risk assessment methods (Braglia et al., 2003). New extended FMEA approaches, by incorporating uncertainty modelling theories like ER, Grey system theory, fuzzy logic and BNs to facilitate their applications in different industries (Yang et al., 2009; Mokhtari et al., 2012; Yang and Wang, 2015; Alyami et al., 2019; Wan et al., 2019a; Liu et al., 2005; Jiang et al., 2019; Cao and Lam, 2019).	The ER approach integrated with model-based fuzzy logic was applied for its superiority in dealing with uncertainty in risk data by using belief structures and synthesizing both incomplete and complete information properly.
Implications	Valuable implications have been drawn by literature from many aspects such as safety and security management (Alyami et al., 2014, 2019; Lu et al., 2022), vulnerability and resilience management (Cao and Lam, 2019; Jiang et al., 2021; John et al., 2016), risk analysis (Chang et al., 2015; Mangla et al., 2015; Nguyen et al., 2019), maritime accidents (Christine et al., 2013; Fan et al., 2020; Feng et al., 2022; Jiang et al., 2020).	The manuscript fulfils the gaps in the risk assessment of the MSC within the context of the MSR regarding the prioritisation of risk events under uncertainties. The valuable implications can be concluded for coastal and ocean management or governance, for future research, for maritime decision management, and for Future direction.

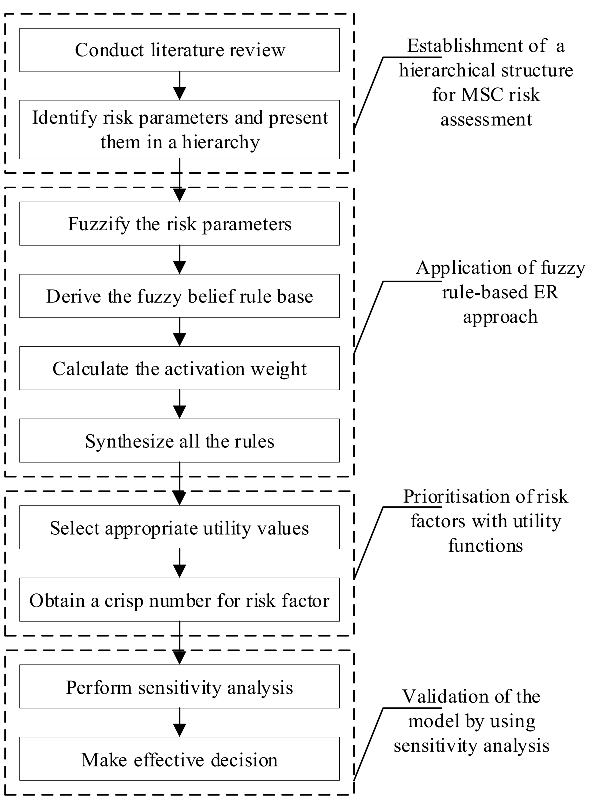

Fig. 1. Framework for risk assessment of MSC.

prevention measures. For example, the additional costs for ransoms demanded by pirates, compensation after a collision, and increased insurance costs. Quality loss describes the loss of any part of the MSC, including the infrastructure of ports, ships at sea, cargoes in transit, and reputation loss. For instance, when ship accidents such as collisions, stranding, and grounding happen during the voyage, the ship, as well as its cargoe will be damaged in part or full. In addition, the transport of dangerous goods has potential impacts on infrastructure, such as explosion and corrosion.

In addition to the likelihood of occurrence and the severity of consequence, risk visibility and controllability are also considered as the two new risk parameters from supply chain/network perspective in this paper. Visibility can be measured by how easily risk events and failures can be detected, which benefits MSCs in terms of transportation efficiency and smoothness (Wan et al., 2019a). In a risk analysis model, the higher a risk event's visibility, the lower the assessed risk of MSC. Risk controllability generally means how easily risk events can be controlled based on a risk analysis result. Therefore, the hierarchical structure framework for MSC risk assessment can be established as shown in Fig. 2.

3.2. Application of fuzzy rule-based ER approach

3.2.1. Determination of the fuzzy input and output variable

Two steps are adopted to determine the fuzzy input and output variables. The first step is to set the granularity of the linguistic terms for each risk parameter, and the second step is to determine the type of the fuzzy membership function of each linguistic term. According to Liu et al. (2005), a granularity from 4 to 7 is generally applied to present risk parameters in risk assessment. It may be difficult to construct fuzzy membership functions due to the lack of information. Linear membership functions like the triangular and the trapezoidal membership functions are usually applied due to their simplicity (Wan, 1997; Yang et al., 2009).

According to the relevant research in the literature and the interpretation of risk parameters presented in the above sections, the linguistic terms for the occurrence, time delay/disruption, financial costs, quality loss, risk visibility, and risk controllability can be determined as follows. The definitions of the four risk parameters (see details in Section 3.1) are shown to the domain experts first. According to the definitions,

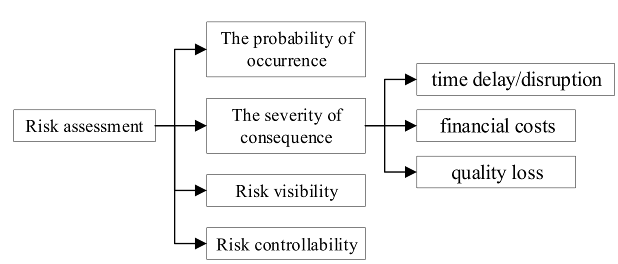

Fig. 2. The structure of risk parameters for the MSCs of the MSR.

the linguistic terms for the likelihood of occurrence and severity of consequence (i.e. time delay/disruption, financial costs, quality loss) have been described by "Very low (VL), Low (L), Medium (M), High (H), Very high (VH)" and "Negligible (N), Slight (SL), Moderate (M), Serious (S), Very serious (VS)", respectively (John et al., 2014). Risk visibility is defined by "Best (B), Good (G), Average (A), Poor (P), Worst (W)" while risk controllability is expressed by "Very easy (VE), Easy (E), Normal (N), Difficult (D), Very difficult (VD)". The risk estimates represented by the fuzzy output are described by "Very low (VL), Low (L), Medium (M), High (H), Very high (VH)". Detailed interpretations for each linguistic term of the four risk parameters are shown in Appendices A-D. They can be illustrated in Figs. 3 and 4 in a generic way (Yang et al., 2009). Although the membership functions of linguistic terms can be flexibly defined to meet various kinds of situations, the support of experts selected appropriately is needed to ensure the authenticity and unbiased membership functions.

3.2.2. Construct a fuzzy rule base using belief structures

A fuzzy rule base with a belief structure (Yang et al., 2009; Liu et al., 2004, 2005) should be proposed to capture the relationship between input and output for reasoning after the identification of risk parameters and the definition of the corresponding linguistic terms. A fuzzy IF-THEN rule with a belief structure is preferred for its superiority in capturing a nonlinear relationship between input and output. The risk parameters are considered as input and the corresponding linguistic terms of risk estimates are considered as output as shown in Eq. (1), which is consisted of two parts: the antecedent and the consequence. Moreover, the antecedent of each fuzzy IF-THEN rule forms a packet antecedent.

$$R_k: \ IF\ A_1^k, \ldots, A_M^k, THEN\ \left\{\left(\beta_1^k, D_1\right), \ldots, \left(\beta_N^k, D_N\right)\right\}\ (k = 1, \ldots, L) \quad (1)$$

where A_i^k ($\forall i \in \{1, \ldots, M\}$) represents the linguistic term of the ith risk parameter of the corresponding attribute in the kth rule (R_k). β_j^k ($\sum_{j=1}^{N}\beta_j^k \le 1$; $\forall j \in \{1, \ldots, N\}$) is the belief degree assigned to D_j, which is the jth consequence of output against the input of A_i^k. L, M, and N represent the number of rules, input and output, respectively.

3.2.3. Calculate the activation weight

The aggregated degrees of all activated antecedents for a rule are called the activation weight of the rule. Before calculating the activation weight, the actual input should be transformed into a distribution representation of the linguistic terms by means of belief degrees. Based on the fuzzy rule base in Eq. (1), the corresponding input in the kth rule for an antecedent risk parameter U_i can be described as Eq. (2).

$$S(U_i) = \left\{\left(A_{ij}, \alpha_{ij}\right); j = 1, \ldots, J_i\right\}, i = 1, \ldots, 5 \quad (2)$$

where A_{ij} means the jth linguistic term of the ith risk parameter, α_{ij} means the belief degree to which A_{ij} belongs to the jth linguistic term with $\alpha_{ij} \ge 0, \sum_j^{J_i}\alpha_{ij} \le 1$ ($i = 1, \ldots, 6$). When generating α_{ij} in Eq. (2), there are various match functions that can be applied. The max-min matching

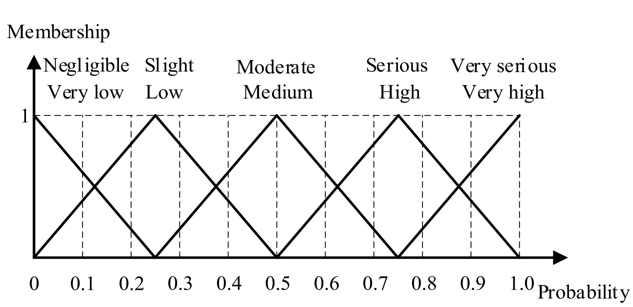

Fig. 3. Fuzzy triangular membership function.

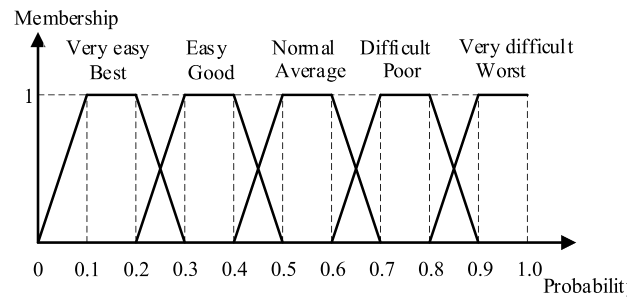

Fig. 4. Fuzzy trapezoidal membership function.

function as shown in Eqs. (3) and (4), is used in this work to identify the correlation between actual input and the corresponding fuzzy linguistic term because it is treated as the most classical tool for fuzzy mapping and applied in many applications (Zimmerman, 1996).

$$\alpha_{ij} = \frac{\varepsilon_i \bullet \tau\left(A_i^*, A_{ij}\right)}{\sum_{j=1}^{J_i}\left[\tau\left(A_i^*, A_{ij}\right)\right]}, i = 1, \ldots, 6; j = 1, \ldots, J_i \quad (3)$$

$$\tau\left(A_i^*, A_{ij}\right) = max\left[\min\left(A_i^*(x), A_{ij}(x)\right)\right] \quad (4)$$

where ε_i is the belief degree of A_i^*, τ represents the max-min matching function, $\tau(A_i^*, A_{ij})$ shows the degree to which A_i^* assigns to A_{ij}.

Then, the activation weight ω_k for the packet antecedent is calculated by using Eqs. (5)–(7) (Liu et al., 2005).

$$\omega_k = (\theta_k.\alpha_k) \Big/ \sum_{i=1}^{L}\theta_i.\alpha_i \quad (5)$$

$$\alpha_k = \prod_{i=1}^{6}\left(\alpha_{i,k}\right)^{\overline{\delta}_i} \quad (6)$$

$$\overline{\delta}_i = \delta_i \Big/ \max_{i=1,\ldots,6}\{\delta_i\} \quad (7)$$

where α_k is the summation of the degree to which the actual input matches to the A_i^k in R_k. δ_i and θ_k mean the weight of the ith antecedent attribute and the relative weight of the kth rule respectively. Note that if the kth rule is not activated, $\omega_k = 0$, and $\sum_{i=1}^{L}\omega_k = 1$.

3.2.4. Synthesize rules using the ER approach

A fuzzy rule base with a belief structure is described in a matrix. The ER method is then applied for rule fusion and obtaining conclusions. First, the belief degree β_j^kshould be transformed into basic probability masses m_D^k, as shown in Eqs. 8–11. The basic probability masses consist of two parts as shown in Eq. (12), one is unassigned probability mass ($\overline{m}_D^k$), while the other is unassigned probability mass ($\widetilde{m}_D^k$) (Liu et al., 2005).

$$m_j^k = \omega_k * \beta_j^k \quad k = 1, \ldots, L\ j = 1, \ldots, N \quad (8)$$

$$m_D^k = 1 - \sum_{j=1}^{N}m_j^k = 1 - \omega_k * \sum_{j=1}^{N}\beta_j^k \quad (9)$$

$$\overline{m}_D^k = 1 - \omega_k \quad (10)$$

$$\widetilde{m}_D^k = \omega_k * \left(1 - \sum_{j=1}^{N}\beta_j^k\right) \quad (11)$$

$$m_D^k = \overline{m}_D^k + \widetilde{m}_D^k \quad (12)$$

where m_j^k is the individual belief degree of R_k belongs to the final conclusion D, ω_k is activation weight for the packet antecedent.

Then, the L rules could be synthesized to generate the fused degree of belief of every activated rule for corresponding $D_j$in D. Define $m_j^{I(k)}$ be the fused belief degree in D_j by fusing the first k packet antecedents and $m_D^{I(k)}$be the rest belief degree unassigned to any D_j. Define $m_j^{I(1)} = m_j^1$ and $m_D^{I(1)} = m_D^1$. Therefore, the synthesized degree of belief β_j of D_j is achieved by Eqs. 13–19.

$$\{D_j\}: \ m_j^{I(k+1)} = K^{I(k+1)} \times \left(m_j^{I(k)} * m_j^{k+1} + m_j^{I(k)} * m_D^{k+1} + m_D^{I(k)} * m_j^{k+1}\right) \quad (13)$$

$$m_D^{I(k)} = \overline{m}_D^{I(k)} + \widetilde{m}_D^{I(k)} \quad k = 1, \dots, L \quad (14)$$

$$\{D\}: \widetilde{m}_D^{I(k+1)} = K^{I(k+1)} \times \left(\widetilde{m}_D^{I(k)} * \widetilde{m}_D^{k+1} + \widetilde{m}_D^{I(k)} * \overline{m}_D^{k+1} + \overline{m}_D^{I(k)} * \widetilde{m}_D^{k+1}\right) \quad (15)$$

$$\overline{m}_D^{I(k+1)} = K^{I(k+1)} \times \left(\overline{m}_D^{I(k)} * \overline{m}_D^{k+1}\right) \quad (16)$$

$$K^{I(k+1)} = \left[1 - \sum_{j=1}^{N} \sum_{\substack{r=1 \\ r \neq j}}^{N} m_j^{I(k)} m_r^{k+1}\right]^{-1}, k = 1, \dots, L-1 \quad (17)$$

$$\{D_j\}: \ \beta_j = m_j^{I(L)} \Big/ \left(1 - \overline{m}_D^{I(L)}\right), j = 1, \dots, N \quad (18)$$

$$\{D\}: \ \beta_D = \widetilde{m}_D^{I(L)} \Big/ \left(1 - \overline{m}_D^{I(L)}\right) \quad (19)$$

where β_D represents the rest unassigned belief degrees to any D_j. The output calculated by combining the L rules is shown as Eq. (20).

$$S(A^*) = \left\{ \left(D_j, \beta_j\right), j = 1, \dots, N \right\} \quad (20)$$

3.3. Prioritisation of risk factors with utility functions

Finally, the results as shown in Eq. (20) describe the risk estimates, which can provide maritime stakeholders with a general opinion on the risk of MSC for each identified risk factor (i.e., the risk events occurred in MSCs). The result of the belief degree that is assigned to the risk parameters and how the risk event influences the MSC can be seen visually. However, it is difficult to visually distinguish the priority of all the risk factors in MSCs by the above results in a distributed way. Therefore, the utility values are proposed to facilitate the process of decision making.

Define $u(D_i)$ $(i = 1, \dots, N)$ is the utility function of D_i. Then the ranking index value V_e $(e = 1, \dots, l)$ for each risk event (i.e., risk factor) can be calculated as follows:

$$V_e = \sum_{i=1}^{N} \beta_j^e \times u(D_i)\Big) \quad (21)$$

where l is the number of risk events in an MSC. Note that $\sum_{e=1}^{l} \beta_j^e = 1$ for the eth risk event. Thus, the ranking for each risk event in an MSC can be determined by the index value.

3.4. Validation of the model by using sensitivity analysis

SA is a powerful technique that can offer useful insights into quantitative assessment to demonstrate the rationality and effectiveness of the proposed model (Contini et al., 2000). This paper applied the SA technique to examine how sensitive the model output is to a slight change in input. In order to verify the reasonability of the approach, the following axioms (Yang et al., 2009) should at least be met.

Axiom 1. A light decrease in the belief degrees of the linguistic terms of risk parameters should lead to a reduction in the risk estimates of the corresponding model output.

Axiom 2. A light increase in the belief degrees of the linguistic terms of risk parameters should lead to an increase in the risk estimates of the corresponding model output.

Axiom 3. A slight decrease or increase in the input data (i.e., the belief degrees of any risk parameters) will certainly lead to the decrement or increment of the overall average scores of the model output correspondingly.

4. Case study

The 21 Century MSR, a part of the BRI is a project initiated by China to establish global maritime transportation networks that enable a more robust and smooth free flow of international trade and commerce. As the important carrier of the MSR, it is important yet necessary to conduct a risk assessment of the involved MSCs to provide the stakeholders with useful insights to make proper decisions. In this paper, the risk factors influencing the MSCs are identified from a multi-perspective including natural environment, social environment, economy, operations, management, and infrastructure, within the context of the MSR. Only those that are of great impact on MSCs are considered due to the complexity and diversity of risk factors. According to the previous research (Wan et al., 2019a, 2019b; Vilko et al., 2019), the most important risk factors, namely “fuel price”, “strikes”, “fierce competition”, “ship accidents”, “transportation of dangerous goods”, and “bottlenecks in routes”, are selected to conduct the case study. Through this case study, such selected risk factors will be quantitatively evaluated and ranked so that the difference among their risk levels can be clearly calculated for rational risk control measure development. This case study is applied to demonstrate the feasibility of the proposed approach in the risk assessment of MSCs.

4.1. Application of the fuzzy ER approach

The ER approach incorporated fuzzy rules is applied to conduct a risk assessment of MSCs in this section. A fuzzy *IF-THEN* rule base with belief degrees, presented in Appendix F, is obtained from experts in the maritime industry. Nguyen et al. (2019) have proved that the scale of experts could be small, but should have a high quality and heterogeneous composition. It will help the study to build a more comprehensive rule base based on the available information from experts with different experience backgrounds (Nguyen, 2020). The experts in this paper are chosen from different companies and different countries with rich experience and highly relevant backgrounds. The details of the invited experts are described in Appendix E. During the selection process, six experts were carefully chosen and screened for their competence. The experts from industries (e.g., senior managers of shipping companies) have extensive experience in supply chain operations, and the academic researchers have well-established theoretical and project experience in ensuring the safety and security of the investigated MSC of the MSR. Further, the captains are capable of dealing with the safety issues about shipping. They all have a wealth of working experience in their respective fields and present a representative and balanced expertise for the survey. Therefore, their impact on the results of risk assessment is equally important. The weights of different experts are assigned the same.

Fuzzy ratings for linguistic terms associated with risk parameters on the basis of the fuzzy membership functions are selected by the six experts. The fuzzy ratings for the risk parameters collected for the risk event “fuel price” are shown in Table 3. The ratings (see Table 3) are transformed into the linguistic terms with belief structures (see Table 4) by using Eqs. (3) - (4), the severity of consequence and the six experts’ judgements are aggregated for further calculation as shown in Table 5. Appendix G shows the aggregated ratings for the other five risk events.

After generating the aggregated fuzzy ratings, the ER method is used

Table 3
Fuzzy ratings of the risk parameters, case of "fuel price".

Expert	Occurrence	Time delay/disruption	Financial costs	Quality loss	Visibility	Controllability
E1	0.8 H, 0.2 VH	0.7 N, 0.3 SL	0.7 S, 0.3 VS	0.6 SL, 0.4 M	0.8 B, 0.2 G	0.1 D, 0.9 VD
E2	[0.8, 1]	[0.1, 0.2]	[0.8, 1]	[0.25, 0.4]	[0.1, 0.3]	[0.9, 1]
E3	(0.8, 0.9, 1)	(0.1, 0.25, 0.3)	(0.8, 0.9, 1)	(0.25, 0.3, 0.4)	(0.2, 0.3, 0.4)	(0.7, 0.9, 1)
E4	0.7 H, 0.3 VH	0.6 N, 0.4 SL	0.8 S, 0.2 VS	0.5 SL, 0.5 M	0.6 B, 0.4 G	1VD
E5	[0.75, 1]	[0.2, 0.4]	[0.8, 1]	[0.3, 0.5]	[0.1, 0.2]	[0.9, 1]
E6	(0.75, 0.9, 1)	(0, 0.25, 0.4)	(0.8, 0.9, 1)	(0.25, 0.3, 0.5)	(0.2, 0.4, 0.5)	(0.8, 0.9, 1)

Table 4
Transformed fuzzy ratings, case of "fuel price".

Expert	Occurrence	Time delay/disruption	Financial costs	Quality loss	Visibility	Controllability
E1	0.8 H, 0.2 VH	0.7 N, 0.3 SL	0.7 S, 0.3 VS	0.6 SL, 0.4 M	0.8 B, 0.2 G	0.1 D, 0.9 VD
E2	0.44 H, 0.56 VH	0.43 N, 0.57 SL	0.44 S, 0.56 VS	0.63 SL, 0.37 M	0.5 B, 0.5 G	1VD
E3	0.44 H, 0.56 VH	0.24 N, 0.65 SL, 0.11 M	0.45 S, 0.55 VS	0.66 SL, 0.34 M	0.33 B, 0.67 G	0.4 D, 0.6 VD
E4	0.7 H, 0.3 VH	0.6 N, 0.4 SL	0.8 S, 0.2 VS	0.5 SL, 0.5 M	0.6 B, 0.4 G	1VD
E5	0.49 H, 0.51 VH	0.11 N, 0.56 SL, 0.33 M	0.44 S, 0.56 VS	0.44 SL, 0.56 M	1 B	1VD
E6	0.47 H, 0.53 VH	0.27 N, 0.54 SL, 0.19 M	0.45 S, 0.55 VS	0.6 SL, 0.4 M	0.18 B, 0.55 G, 0.27 A	1VD

Table 5
Aggregated fuzzy ratings, case of "fuel price".

Expert	Occurrence	Consequence	Visibility	Controllability
E1	0.79 H, 0.21 VH	0.23 N, 0.24 SL, 0.19 M, 0.23 S, 0.11 VS	0.8 B, 0.2 G	0.1 D, 0.9 VD
E2	0.44 H, 0.56 VH	0.14 N, 0.43 SL, 0.12 M, 0.14 S, 0.17 VS	0.5 B, 0.5 G	1VD
E3	0.44 H, 0.56 VH	0.07 N, 0.47 SL, 0.15 M, 0.14 S, 0.17 VS	0.33 B, 0.67 G	0.4 D, 0.6 VD
E4	0.69 H, 0.31 VH	0.19 N, 0.32 SL, 0.16 M, 0.26 S, 0.07 VS	0.6 B, 0.4 G	1VD
E5	0.51 H, 0.49 VH	0.03 N, 0.35 SL, 0.31 M, 0.14 S, 0.17 VS	1 B	1VD
E6	0.47 H, 0.53 VH	0.08 N, 0.41 SL, 0.2 M, 0.14 S, 0.17 VS	0.18 B, 0.55 G, 0.27 A	1VD
Aggregated linguistic terms	0.57 H, 0.43 VH	0.12 N, 0.4 SL, 0.18 M, 0.17 S, 0.13 VS	0.59 B, 0.37 G, 0.04 A	0.06 D, 0.94 VD

to calculate the risk estimates. In the case of "fuel price", sixty rules are activated according to the aggregated linguistic terms. The activation weights ω_k are obtained for the rules in the fuzzy rule base through Eqs. (5)–(7). Then, the ER algorithm presented in Eqs. 8–20 are used to synthesize the sixty rules to obtain the risk estimates. As shown in Fig. 5, the result of the risk factor "fuel price" is {"Very low", 16.97%, "Low", 18.95%, "Medium", 5.14%, "High", 19.61%, "Very high", 39.32%}, which can be interpreted as the risk levels of the "fuel price" being estimated as "Very low" with a belief degree of 0.1697, "Low" with a belief degree of 0.1895, "Medium" with a belief degree of 0.0514, "High" with a belief degree of 0.1961, and "Very high" with a belief degree of 0.3932.

In order to rank the risk levels of each of the six selected top risk factors in MSCs, the utility value of each grade is linearly defined as "Very low" is 0, "Low" is 0.25, "Medium" is 0.5, "High" is 0.75, and "Very high" is 1. The assigned utility values indicate that the higher the risk-utility value, the worse the risk situation the risk factor/event. The ranking results for the risk events that could occur in the MSCs are generated by using the Eq. (23) Eq. (23) as shown in Fig. 6. The risk event of "fuel price" obtains the highest rank, which means the risk situation is the worst.

4.2. Sensitivity analysis

SA is employed to validate the changes in risk estimates in the presence of changes in fuzzy inputs. This process can be accomplished by using the axioms in Section 3.4. The adoption of the above axioms will facilitate the identification of the significant risk factors that could occur in MSCs and the improvement of the robustness of the developed model. To carry out the SA, the software contained programs called IDS is applied to fusion the information. IDS software is a mature commercial package, requiring no high-performance computer to run. In order to carry out Axiom 1 and Axiom 2, 5% of belief degrees assigned to each linguistic term of risk parameters is decreased or increased because the model is developed with a high sensitivity to small changes due to this accuracy and robustness. The changed results of the risk estimates for each risk event can be seen in Fig. 7. The risk distributions are stable and consistent for the risk events of fuel price, strikes, fierce competition, ship accidents, and transportation of dangerous goods in Fig. 7, which reveals the robustness of the model. For the risk event of bottlenecks in routes, small differences are found in the consequence. However, the fluctuation of the risk parameter of "controllability" for the risk events "bottlenecks in routes" is only about 2%, and its score is still in harmony with Axiom 2, and within a controllable range. The results of the consistency and difference aid to validate the approach and prove that it is robust yet sensitive to small changes.

According to the results generated from the proposed model, as presented in Fig. 6, the risk score of risk event "fuel price" was assessed as 0.6134 derived previously from the IDS software. In Axiom 3 the gradual change of the score for the risk event "fuel price" has been compared to 0.6134 as a baseline because of its high ranking in the evaluation. In the case of "fuel price" the belief degrees for each risk parameter were changed under the same conditions and the new utility values of the risk estimates were recorded. In Fig. 8, the most sensitive risk parameter is controllability, followed by occurrence and consequence. It emphases the importance of incorporation of controllability in this analysis and hence further justify the choice of the risk parameters in the risk model.

4.3. Research implications

The purpose of the study is to fulfil the gaps in the risk assessment of the MSC within the context of the MSR regarding the prioritisation of risk events under uncertainties. To be specific, risk parameters are proposed on the basis of the literature review and features of MSCs to measure the selected risk events in a systematic manner. The fuzzy ER approach is applied to conduct a risk assessment and is validated by SA.

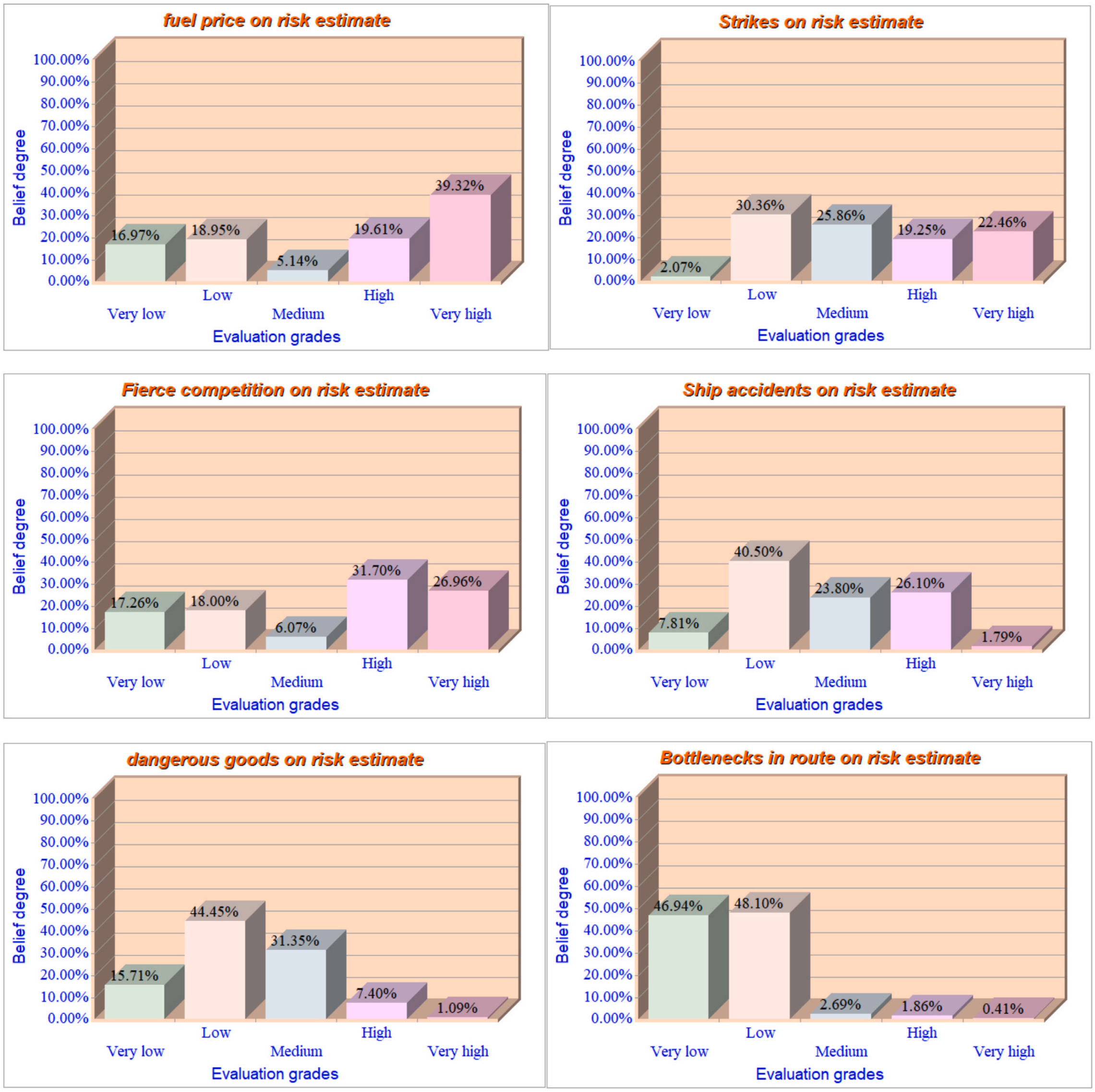

Fig. 5. Risk estimates for risk fa16.ctors of MSCs.

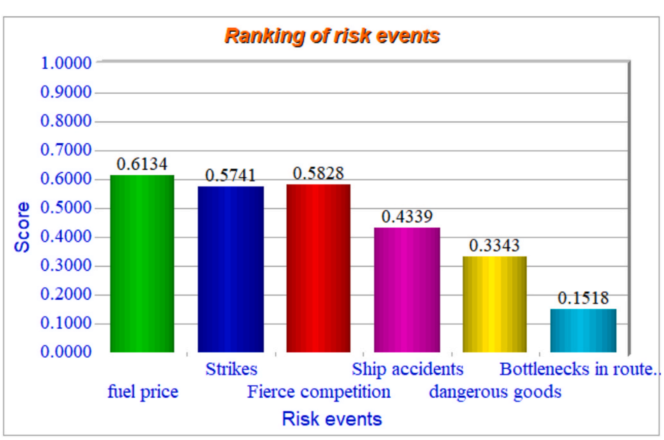

Fig. 6. Ranking results of the risk factors.

It should be well noted that the valuable implications are concluded as follows.

(1) Implications for coastal and ocean management or governance. By ranking the risk factors affecting the MSCs, the results can guide the ocean and coastal management sector to adjust and enhance the adaptation against risk events to ensure the sustainable development of coastal ports. Furthermore, the government bodies, such as the Ministry of Natural Resource and Ministry of Transport, can use the findings to effectively design prevention measures. For instance, Ministry of Natural Resource can formulate relevant policies to ensure the development of the marine transportation industry (e.g., ocean capacity supply, coastal port production, etc.) on the basis of the analysis results. Logistics and shipping companies can use the findings to adjust and rationalise their safety investment and ensure such investment is always in a proportion to the risk levels. Therefore, their risk management could become much more scientific and cost-effective. As a result, it will improve their financial sustainability and social sustainability when taking into account the possible reputation loss due to the occurrence of any accident. More importantly, the findings can be tailored to fit different MSCs of

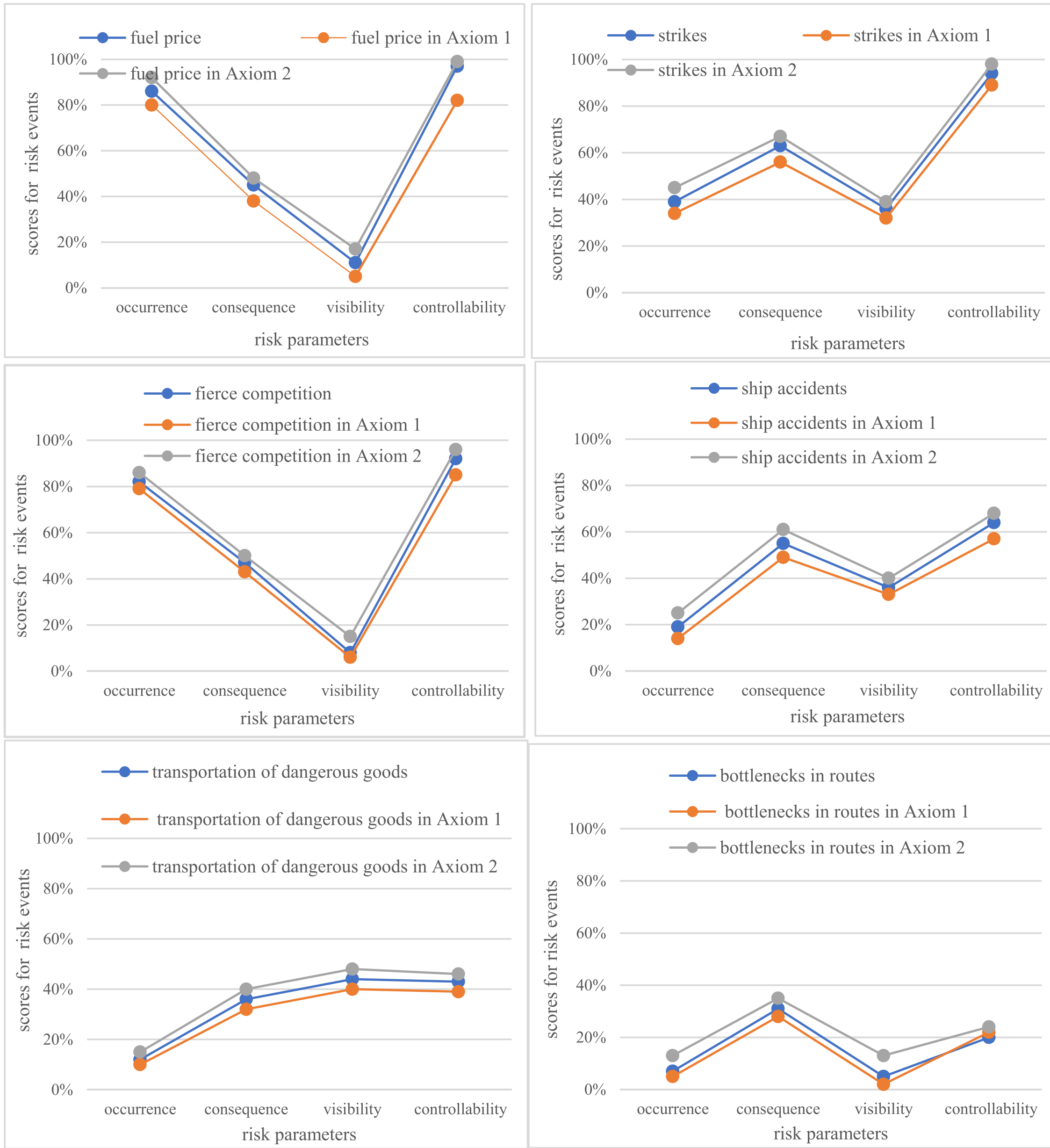

Fig. 7. Influence of slight changes in belief degrees on the risk estimates of the model output.

diversified risk events of various kinds of features. It is because of the generality that the model and newly applied approach will enable the shipping companies and logistics providers in a more competitive position compared to those who fail to use it. It can be applied by and benefit a single stakeholder/participant (seaport) of an MSC or all the involved parties in the chain with a logistic company providing an overall solution, to the risk events ranging from transport infrastructure to operational, managerial, and financial aspects. From this perspective, the findings will aid to significantly improving the resilience and sustainability of coastal states (ports) and oceans (shipping transport) associated with the MSR, the world's largest economic corridor of strategic importance.

(2) Theoretical implications for future research. The approach integrating a fuzzy rule base and ER provides researchers with a useful tool to deal with qualitative data to assess risks and priorities risk events under uncertainties based on the MSCs of their interest. In the proposed approach, the ratings from experts assigned the defined linguistic terms with a belief structure have been introduced to handle incompleteness in data. To be specific, the proposed approach overcomes the deficiencies of losing important information in the fuzzy risk estimate process. Furthermore, the ER approach shows its superiority in fusing various formats of information. It also for the first time, incorporates new risk parameters at different tiers of a hierarchy for MSC risk assessment, in which the risk factors are identified from a multiple perspective involving operational, financial and environmental concerns.

(3) Managerial implications for maritime decision makers. The framework helps to generate useful implications for maritime decision makers such as shipping companies, ports, port states, and shippers to guarantee the connectivity and robustness of the MSCs. Firstly, when using the developed model, shipping companies or port operators can rank the risk factors they face and increase their understanding of MSCs operations involving different risk factors. Specifically, shipping companies can use it to plan routes, select ports and set liner pricing. For instance, the case study indicates that the risk event "fuel price" is the most

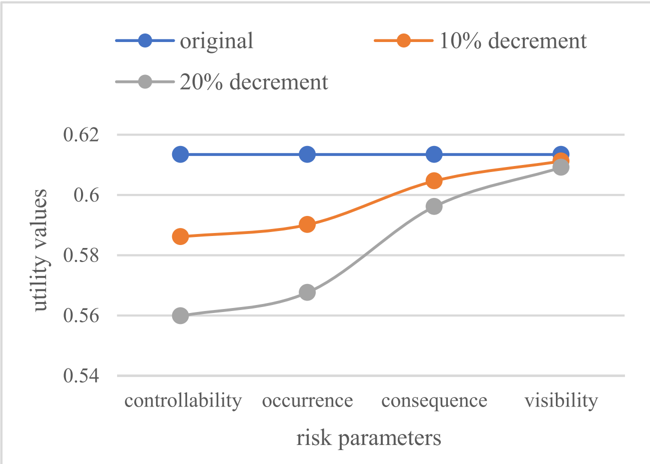

Fig. 8. Effect of changes in the input data on overall average scores of the model output to fulfil the Axiom 3.

important one influencing MSCs of the MSR, followed by "strike", shipping companies could assign more preference to these ports with relatively cheap fuel prices and politically stable situation when considering the calling ports of liners based on the results. Secondly, it presents the results through a careful way of survey. Different stakeholders of MSCs can use it as an indicator of risk levels for risk monitoring and accident prevention. For instance, the prioritisation of risk events based on the case study provides rich information for a shipping company in regard to different requirements in the decision-making process and is helpful to allocate limited safety resources to the highest-impact risk events.

(4) Future direction implications. The study proposed a generic and standard framework for risk assessment of MSC within the context of the MSR. Although it is validated and demonstrated by sensitivity analysis in the maritime industry, it has the possibility to be adopted in other applications in various supply chains by rebuilding the structure and new rule base to fit the new demands, including the emerging hot topics such as the online retailing strategy choice (Chen et al., 2022a, 2022b), supply chain management (Peng et al., 2022), etc.

5. Conclusions

A novel MSC risk assessment model is developed based on a fuzzy ER approach, where the fuzzy logic is used to represent the input information under uncertainties of all the MSC risk parameters, and the ER approach is used to conduct risk inference and synthesize various information in a new two-tier risk parameter hierarchy. The new risk hierarchy not only separates the severity of consequence into three sub-level parameters but also incorporates new risk parameters such as risk visibility and controllability. It brings significant theoretical contributions on supply chain risk assessment from a single node towards a network systematic analysis and from a risk oriented towards a resilience analysis. Its key contributions from an applied research perspective involving MSC included that 1) it presents a pioneering work to analyse MSC risks from the perspective of the implementation of MSR. This paper develops knowledge in terms of the multi-dimensional selection of risk parameters within the MSR context; 2) it proposes a powerful approach to assessing MSC risks under uncertainty that enriches the existing research field of risk assessment; and 3) it introduces a generic way to integrate the fuzzy ER and the associated calculation software IDS, which shed light on decision makings for maritime stakeholders.

At the same time, there are limitations to be further addressed, among which the most significant is that the MSR development involves many countries, and more experts from the involved countries could be invited to make the findings more representative.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Probability of occurrence interpretation

Fuzzy number	Probability of occurrence	Interpretation
(0, 0, 0.25)	Very low	Probability of the risk event occurrence is 0%–25%
(0, 0.25, 0.5)	Low	Probability of the risk event occurrence is 0%–50%
(0.25, 0.5, 0.75)	Medium	Probability of the risk event occurrence is 25%–75%
(0.5, 0.75, 1)	High	Probability of the risk event occurrence is 50%–100%
(0.75, 1, 1)	Very high	Probability of the risk event occurrence is 75%–100%

Appendix B. Severity of occurrence interpretation

Fuzzy number	Severity of occurrence	Interpretation
(0, 0, 0.25)	Negligible	The risk event output has caused 0%–25% of the loss in time, finance or quality
(0, 0.25, 0.5)	Slight	The risk event output has caused 0%–50% of the loss in time, finance or quality
(0.25, 0.5, 0.75)	Moderate	The risk event output has caused 25%–75% of the loss in time, finance or quality

(*continued on next page*)

(*continued*)

Fuzzy number	Severity of occurrence	Interpretation
(0.5, 0.75, 1)	Serious	The risk event output has caused 50%–100% of the loss in time, finance or quality
(0.75, 1, 1)	Very serious	The risk event output has caused 75%–100% of the loss in time, finance or quality

Appendix C. Risk visibility interpretation

Fuzzy number	Risk visibility	Interpretation
[0, 0.1, 0.2, 0.3]	Best	0%–30% of the risk event cannot be identified before occurring through risk checks
[0.2, 0.3, 0.4, 0.5]	Good	20%–50% of the risk event cannot be identified before occurring through risk checks
[0.4, 0.5, 0.6, 0.7]	Average	40%–70% of the risk event cannot be identified before occurring through risk checks
[0.6, 0.7, 0.8, 0.9]	Poor	60%–90% of the risk event cannot be identified before occurring through risk checks
[0.8, 0.9, 1. 1]	Worst	80%–100% of the risk event cannot be identified before occurring through risk checks

Appendix D. Risk controllability interpretation

Fuzzy number	Risk controllability	Interpretation
[0, 0.1, 0.2, 0.3]	Very easy	0%–30% of the risk event cannot be controlled well after occurring
[0.2, 0.3, 0.4, 0.5]	Easy	20%–50% of the risk event cannot be controlled well after occurring
[0.4, 0.5, 0.6, 0.7]	Normal	40%–70% of the risk event cannot be controlled well after occurring
[0.6, 0.7, 0.8, 0.9]	Difficult	60%–90% of the risk event cannot be controlled well after occurring
[0.8, 0.9, 1. 1]	Very difficult	80%–10% of the risk event cannot be controlled well after occurring

Appendix E. Experts profile

Expert no.	Country or company name	Title and department	Experience and professional background
1	COSCO Shipping, China	Senior manager, operation department	The expert has been engaged in maritime supply chain for 10 years in the current shipping company
2	MAERSK line, Denmark	Senior manager, operation department	The expert has been engaged in maritime supply chain for 15 years of with two shipping companies
3	Dalian Maritime University, China	Academic researchers, MSR department	The expert has been engaged in maritime safety and security within the context of the Maritime Silk Road for 16 years in a research institute
4	Dalian Maritime University, China	Professor, Transportation planning and management department	The expert has worked in university for 20 years and has rich experience in safety and security of the MSR.
5	COSCO Shipping, China	Captain, shipping company	The expert has 12 years of on-board experience in ocean navigation between Asia and Europe
6	MAERSK line, Denmark	Captain, shipping company	The expert has 15 years of on-board experience, including 6 years as a captain; 4 years as training crew members

Appendix F. The established fuzzy rules with belief structures

Rule no	Risk parameters				Risk estimate				
	Occurrence	Consequence	Visibility	Controllability	Very low	Low	Medium	High	Very high
1	Very low	Negligible	Best	Very easy	1	0	0	0	0
2	Very low	Negligible	Best	Easy	0.9	0.1	0	0	0
3	Very low	Negligible	Best	Normal	0.8	0.2	0	0	0
4	Very low	Negligible	Best	Difficult	0.4	0.4	0.2	0	0
5	Very low	Negligible	Best	Very difficult	0	0.5	0.5	0	0
…	…	… …	…	…	…	…	…	…	…
248	Low	Very serious	Worst	Normal	0	0.2	0.7	0.1	0
249	Low	Very serious	Worst	Difficult	0	0.2	0.5	0.3	0
250	Low	Very serious	Worst	Very difficult	0	0.2	0.3	0.5	0
251	Medium	Negligible	Best	Very easy	0	0.8	0.2	0	0
252	Medium	Negligible	Best	Easy	0	0.7	0.3	0	0
…	…	… …	…	…	…	…	…	…	…
498	High	Very serious	Worst	Normal	0	0	0	0.3	0.7
499	High	Very serious	Worst	Difficult	0	0	0	0.2	0.8
500	High	Very serious	Worst	Very difficult	0	0	0	0.1	0.9
501	Very high	Negligible	Best	Very easy	0	0.6	0.4	0	0
502	Very high	Negligible	Best	Easy	0	0.5	0.5	0	0
…	…	… …	…	…	…	…	…	…	…

(*continued on next page*)

(*continued*)

Rule no	Risk parameters				Risk estimate				
	Occurrence	Consequence	Visibility	Controllability	Very low	Low	Medium	High	Very high
221	Very high	Very serious	Worst	Very easy	0	0	0.5	0.5	0
622	Very high	Very serious	Worst	Easy	0	0	0.2	0.3	0.5
623	Very high	Very serious	Worst	Normal	0	0	0	0.2	0.8
624	Very high	Very serious	Worst	Difficult	0	0	0	0.1	0.9
625	Very high	Very serious	Worst	Very difficult	0	0	0	0	1

Appendix G. Aggregated fuzzy inputs for further calculations

Risk event	Occurrence	Consequence	Visibility	Controllability
Strikes	0.43 L, 0.57 M	0.09 N, 0.13 SL, 0.14 M, 0.46 S, 0.18 VS	0.62 G, 0.31 A, 0.07 P	0.25 D, 0.75 VD
Fierce competition	0.73 H, 0.27 VH	0.05 N, 0.42 SL, 0.25 M, 0.17 S, 0.11 VS	0.68 B, 0.31 G, 0.01 A	0.32D, 0.68 VD
Ship accidents	0.23 VL, 0.77L	0.11 N, 0.17 SL, 0.22 M, 0.42 S, 0.08 VS	0.62 G, 0.31 A, 0.07 P	0.43 N, 0.57 D
Transportation of dangerous goods	0.53 VL, 0.47L	0.16 N, 0.45 SL, 0.22 M, 0.12 S, 0.05 VS	0.45 G, 0.34 A, 0.21 P	0.29 E, 0.71 N
Bottlenecks in route	0.72 VL, 0.28L	0.12 N, 0.65 SL, 0.12 M, 0.09 S, 0.02 VS	0.82 B, 0.17 G, 0.01 A	0.21 VE, 0.79 E

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