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Societal risk acceptance criteria of the global general cargo ships

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ABSTRACT

The societal risk acceptance criteria (SRAC) are used in the shipping industry as a ruler to judge whether the actual ship risk is in control. To exploringly refresh SRAC for general cargo ship formulated by International Maritime Organization (IMO) in 2000, a comprehensive analysis was performed by using the accident data recorded in the Marine Casualties and Incidents (MCI) module of the Global Integrated Shipping Information System (GISIS) database from 2005 to 2019. The risk levels of four typical accident factors, including initial event, ship size, classification society, and geographical zone, were evaluated. The results illustrate that the SRAC established in this study for general cargo ship fatality accidents are found stricter than that by IMO presented in 2000. Fire/explosion and capsizing show the highest societal risk levels in the initial events, and large general cargo ships face higher societal risk. In addition, ships that do not belong to the International Association of Classification Societies (IACS) are at a higher risk than IACS ships. And the societal risk levels of fatality accidents in East & Southeast Asia and injury accidents in Europe, the Mediterranean & Black Sea are higher than those in the other zones.

1. Introduction

With the ongoing development of the shipping industry, particularly the advent of container ships, the ability to aggregate shipments into a standardized carriage has rapidly increased (Yang et al., 2005; Zhang et al., 2020; Yu et al., 2021; B. Liu et al., 2021). However, some specialized or more general cargoes are not suitable to be transported through standardized boxes, while those general cargo ships can provide a more bespoken carriage service. Statistics showed that the general cargo ships' seaborne trade has increased nearly 27 times in the past 40 years (Sirimanne et al., 2020; Khan et al., 2021; Zhang et al., 2021a, 2021b). General cargo ships play an important role in the shipping industry. The number of general cargo ships accounts for 13.9% of the world's merchant fleet, which is higher than bulk carriers (10.2%), passenger ships (6.3%), and container ships (4.5%) (Equasis, 2019).

Shipping activities are always in a complex and risky environment (Chen et al., 2017; Van Hoof et al., 2020; Kamal and Kutay, 2021; K. Liu et al., 2021), and general cargo ship accidents frequently occur, causing massive economic losses and casualties. Despite adopting a series of navigation safety policies and regulations and improving training, technology, and risk management (Chen et al., 2019; Rangel-Buitrago et al., 2020; Little et al., 2021; Perillo et al., 2021), the number of accidents related to general cargo ships still accounts for a large proportion. Historical data show that general cargo ships are the main category involved in a marine casualty or incident (43.8%) from 2011 to 2018, and accidents have risen in recent years (EMSA, 2019). As the world's hydrological conditions change and sea transport traffic increases, particularly in narrow waters, navigational waters are becoming more complex and inconsistent, increasing navigation risk (Ozturk and Cicek, 2019; McWhinnie et al., 2021; Morelli et al., 2021).

Studies have shown that various risk factors may exist during ship navigation and transportation, and these risk factors influence ship safety (Chen et al., 2018; Tan et al., 2021). However, the societal risk levels of various factors in the general cargo ship accidents remain

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Table 1
Descriptive statistics of fatality and injury factors in general cargo ship accidents.

Factors / Items	Attributes	Mean	Stdev
Initial event			
Capsizing	1 if a capsizing occurs, 0 otherwise	0.105	0.307
Collision	1 if a collision occurs, 0 otherwise	0.258	0.438
Contact	1 if a contact occurs, 0 otherwise	0.074	0.262
Fire/explosion	1 if a fire/explosion occurs, 0 otherwise	0.115	0.319
Hull failure	1 if a hull failure occurs, 0 otherwise	0.028	0.164
Mechanical failure	1 if a mechanical failure occurs, 0 otherwise	0.070	0.255
Missing	1 if a missing occurs, 0 otherwise	0.015	0.122
Ship or equipment damage	1 if a ship or equipment damage occurs, 0 otherwise	0.039	0.193
Stranding/ grounding	1 if a stranding/grounding occurs, 0 otherwise	0.284	0.451
Others	1 if other initial events occur, 0 otherwise	0.013	0.111
Ship size			
Small ship	1 for small ships (<500 GT), 0 otherwise	0.065	0.247
Medium ship	1 for medium ships (500 $\leq$ GT < 2,000), 0 otherwise	0.292	0.455
Large ship	1 for large ships ($\geq$2,000 GT), 0 otherwise	0.643	0.479
Classification society			
IACS	1 if classification society belongs to IACS, 0 otherwise	0.314	0.464
Non-IACS	1 if classification society belongs to non-IACS, 0 otherwise	0.686	0.464
Geographical zone	1 if the accident occurred in the region i, 0 otherwise ($i = 1, \ldots, 11$)	2.189	1.728

unknown. To better assess the risk of the general cargo ships, it is necessary to establish reasonable societal risk acceptance criteria (SRAC) and determine the societal risk levels of those influencing factors.

This paper collects and pre-processed the global general cargo ship accident data, and established the SRAC for general cargo ship fatality and injury accidents by employing the as low as reasonably possible (ALARP) principle and F–N curve. Then, the fatality and injury societal risk levels of the initial event, ship size, classification society, and geographical zone were assessed. The spatial risk distribution of these accident factors was identified. This study's contribution is primarily reflected in three aspects. Firstly, this study comprehensively evaluates the societal risk level of fatality and injury accidents. Secondly, this study provides a valuable tool to establish the SRAC of maritime accidents. Thirdly, the findings of this study serve as a decision-making reference for those international organizations, relevant governments, and policymakers to develop reasonable and effective governance strategies for general cargo ships.

2. Literature review

The Formal Safety Assessment (FSA) guideline was developed to assist the International Maritime Organization (IMO) and other policymakers in formulating policies and regulations on the maritime safety and protection of the marine environment (IMO, 2002; Kontovas and Psaraftis, 2009; Wang, 2001). The guideline was further revised by MSC/Circ.1180-MEPC/Circ.474 (IMO, 2005), MSC-MEPC.2/Circ.12 (IMO, 2013), MSC-MEPC.2/Circ.12/Rev.1 (IMO, 2015), and MSC-MEPC.2/Circ.12/Rev.2 (IMO, 2018). In addition, recent FSA developments have focused on the IMO level. For example, the FSA guidelines and the HEAP (Human Element Analyzing Process) guidelines were revised at the 90th Maritime Safety Committee (MSC) session (IMO, 2012). The draft amended flow chart was proposed at the 98th MSC session (IMO, 2017). The risk assessment criteria for identifying safety issues were reviewed at the 101th MSC session (IMO, 2019). The recent MSC session reviewed the FIRESAFE I and II studies commissioned by the European Maritime Safety Agency (EMSA) to address fires on ro-ro passenger ships (IMO, 2021).

A host of FSAs on ship safety have been submitted and reviewed by the IMO over the last few decades, such as liquefied natural gas (LNG) carriers [MSC 83/21/1 and MSC 83/INF.3], container vessels [MSC 83/21/2 and MSC 83/INF.8], crude oil tankers [MEPC 58/17/2 and MEPC 58/17/INF.2], cruise ships [MSC 85/17/1 and MSC 85/INF.2], RoPax ships [MSC 85/17/2 and MSC 85/INF.3], and general cargo ships [MSC 88/19/2, MSC 88/INF.6, and MSC 88/INF.8] (Psaraftis, 2012). Furthermore, SAFEDOR, as an EU-funded research project, has conducted some FSAs to propose risk control options to improve the safety of certain ships. Despite its attractiveness, the research revealed that FSA still has some deficiencies (*e.g.*, unavailable failure data, unjustified expert options, and floating risk criteria) and concerns in its practical

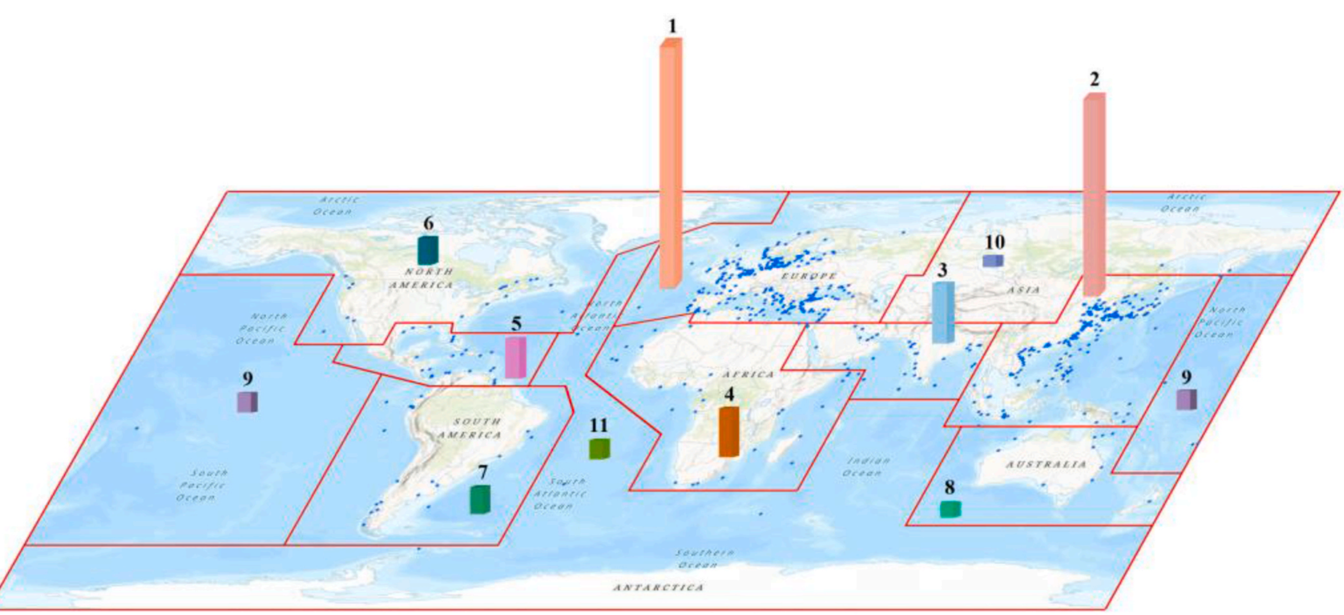


Fig. 1. Accident frequencies of global general cargo ships in different geographical regions (1-Europe, the Mediterranean & Black Sea, 2-East & Southeast Asia, 3-South Asia, 4-Africa, 5-Middle America & Gulf of Mexico, 6-North America, 7-South America, 8-Australia & New Zealand, 9-Pacific Ocean, 10-North Asia, 11-Others).

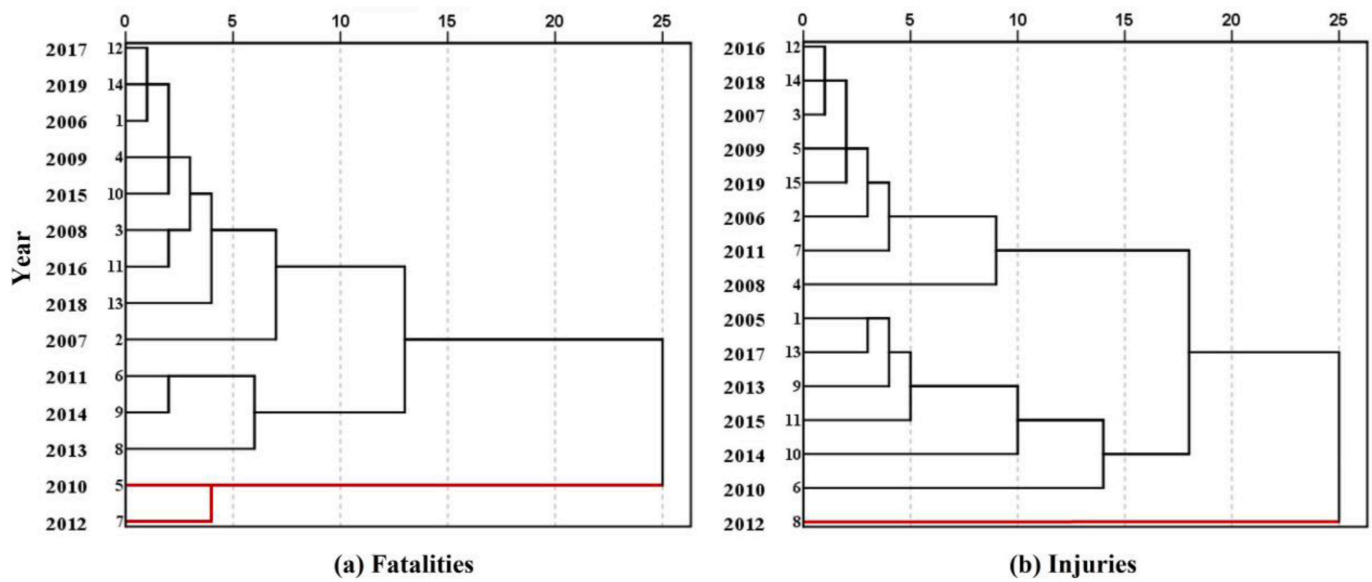


Fig. 2. Dendrogram of fatalities and injuries using between-groups average linkage.

Table 2
Linear regression analysis results of fatalities and injuries.

Classification	Model Summary		Coefficients		ANOVA						
	R	R^2	St. Error of the estimate (S_e)	Model	Unstandardized coefficients		Standardized coefficients	t	t-Sig.	F	F-Sig.
					B	St. Error	Beta				
Fatalities	0.903	0.815	0.292024	(Constant)	−2.601	0.172	−0.903	−15.106	0.000	110.780	0.000
				$\log_{10} N$	−1.650	0.157		−10.525	0.000		
Injuries	0.955	0.912	0.150178	(Constant)	−3.843	0.092	−0.955	−41.597	0.000	218.631	0.000
				$\log_{10} N$	−1.319	0.089		−14.786	0.000		

Table 3
The equations of the criterion lines of F–N diagram of fatalities and injuries.

Classification	Equation
Fatalities	$\log_{10} F(N) = -1.650\log_{10} N - 2.061$
Injuries	$\log_{10} F(N) = -1.319\log_{10} N - 3.843$

Table 4
The equations for the intolerable and negligible lines of fatalities and injuries.

Classification	Risk lines	Equations
Fatalities	Intolerable line	$\log_{10} F(N) = -1.650\log_{10} N - 2.028$
	Negligible line	$\log_{10} F(N) = -1.650\log_{10} N - 3.173$
Injuries	Intolerable line	$\log_{10} F(N) = -1.319\log_{10} N - 3.548$
	Negligible line	$\log_{10} F(N) = -1.319\log_{10} N - 4.137$

applications (Yang et al., 2013; Yang and Wang, 2008).

Currently, many researchers have conducted FSA studies in marine safety. For example, Wang and Foinikis (2001) conducted a statistical analysis of container ship accidents and proposed an FSA methodology for container ships. Lois et al. (2004) discussed the development and applicability of FSA in the cruise shipping industry. Hu et al. (2007) researched the quantitative risk assessment and generic risk model in FSA. Skjong (2011) reviewed the IMO's implementation of FSA in the regulatory system for ships. Psaraftis (2012) presented a review of the FSA method and made some suggestions for further FSA research. Zhang et al. (2013) estimated the Yangtze River's navigational risk using the FSA and Bayesian network (BN) technique. Görçün and Burak (2015) applied FSA methodology to analyze risks associated with marine traffic in the Bosphorous Strait. Yang and Qu (2016) proposed a novel quantitative maritime security assessment framework capable of accommodating new security risk assessment and mitigation methods using uncertainty modeling techniques. Asuelimen et al. (2020) proposed an application of FSA to reduce accidents in marine seismic surveying and identified critical risk factors that lead to marine seismic survey accidents in the North Sea. Wang et al. (2020) developed a novel approach based on the FSA procedure for assessing the safety level of a battery-powered high-speed catamaran. The above academic researches show that the FSA studies on maritime safety primarily focus on specific ships or geographical areas, laying a good foundation for general cargo ship accident analysis in this paper.

Risk assessment is a critical component of the FSA procedures. Since the IMO introduced FSA as a tool for rulemaking, risk assessment has gained widespread attention in maritime safety(Chen et al., 2021; Kotrikla et al., 2021; Su and Peng, 2021). Vanem et al. (2008) conducted a risk assessment of the global operation of ocean-going LNG carriers and indicated that the collision risk is the highest. Olita et al. (2012) proposed a coastal finite element model to assess the hazard and risk of oil spills along the shorelines of a Mediterranean coastal archipelago. Youssef et al. (2014) conducted a risk assessment for double-hulled oil tankers involved in collisions with different types of ships. Vidmar and Perkovič (2015) assessed the risk levels of different types of accidents for cruise ships in port. Chen et al. (2017) presented a fuzzy matter element method for evaluating the main contributing factors of world total-loss marine casualty, which used matter, characteristics, and fuzzy value as the basic elements for the description of things, so as to carry out the quantitative calculation and qualitative analysis of the characteristics or

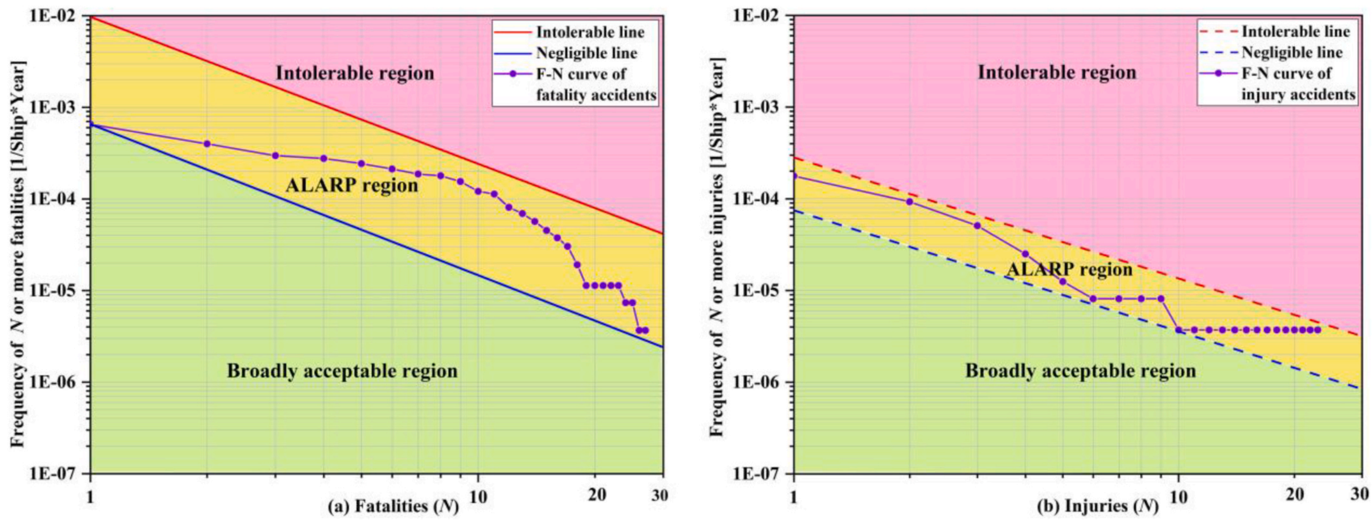


Fig. 3. SRAC of general cargo ships.

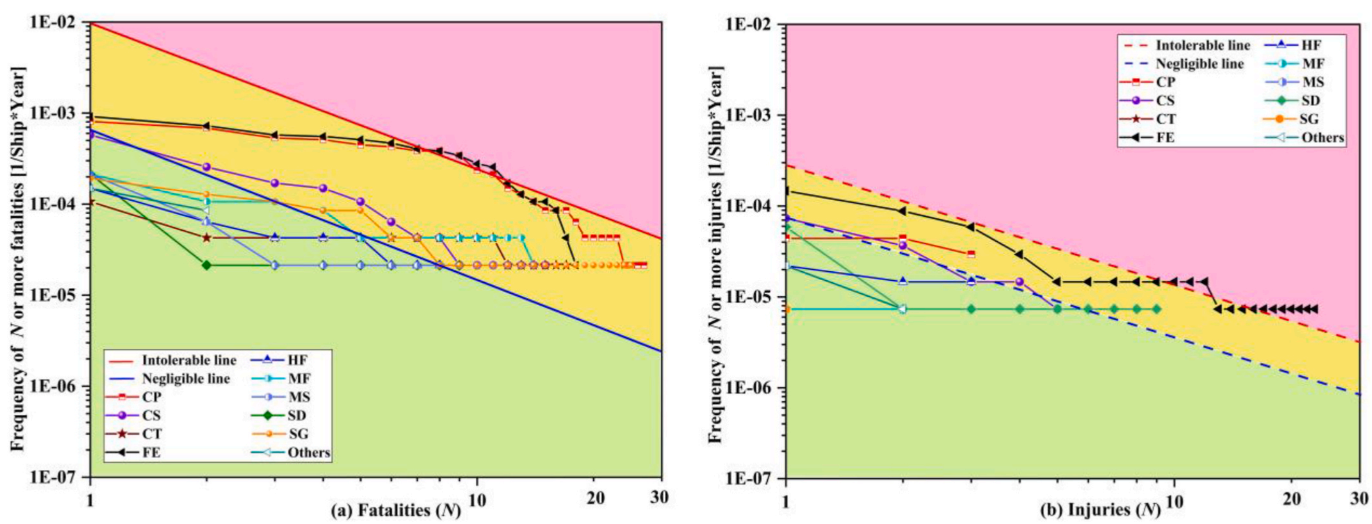
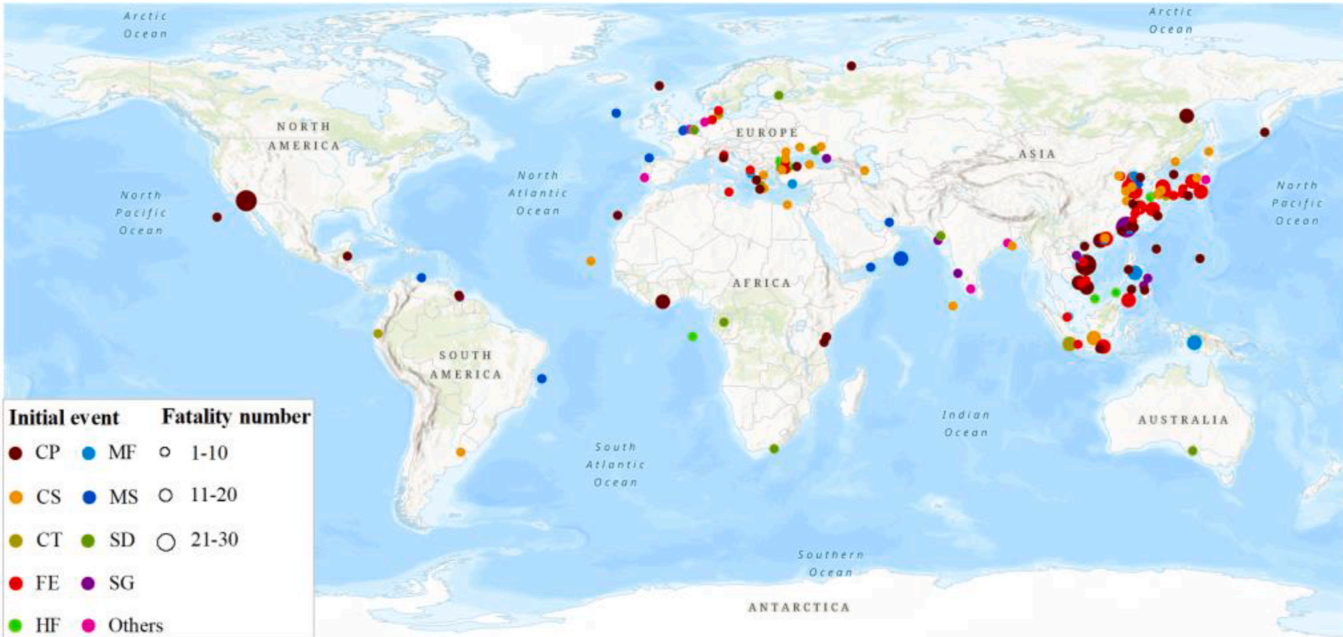


Fig. 4. Societal risk levels based on different initial events (Capsizing-CP, Collision-CS, Contact-CT, Fire/explosion-FE, Hull failure-HF, Mechanical failure-MF, Missing-MS, Ship or equipment damage-SE, Stranding/grounding-SG).

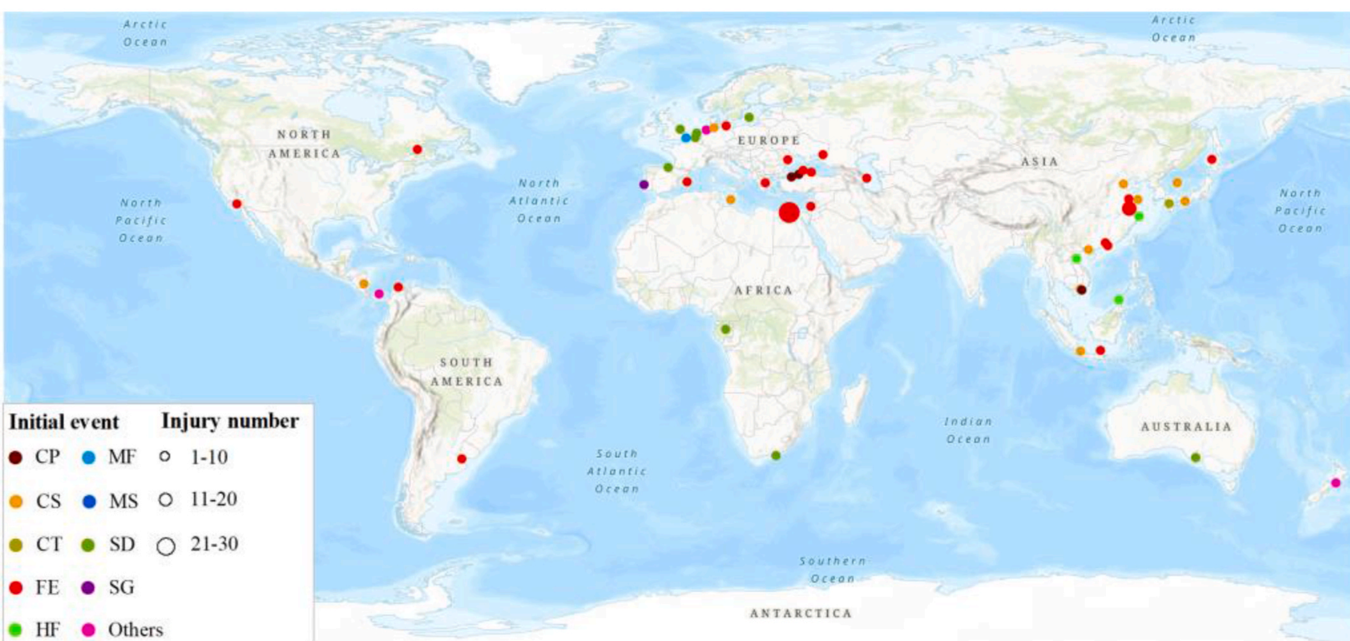
indicators of the matter. Vidmar and Perkovič (2018) investigated three risk levels (*i.e.*, lives, containment, and property) of crude oil tanker accidents. Chen et al. (2019) developed an improved entropy weight-TOPSIS (Technique for Preference by Similarity to Ideal Solution) model to examine the risk factors that influence total-loss marine accidents worldwide. Chen et al. (2020b) evaluated dangerous goods accidents at China's ports using formal concept analysis and created a concept lattice model of dangerous goods accidents. Hoof et al. (2020) designed a common framework for the risk assessment of multi-use at sea.

In addition to the methods mentioned above, researchers have used other methods to assess the risk of maritime safety (Zhang et al., 2019a), such as the fuzzy rule-based Bayesian reasoning approach (Yang et al., 2010), spatial vulnerability approach (Nelson et al., 2015), fault tree analysis (Uğurlu et al., 2015), Zero-Inflated Negative Binomial regression model (Weng et al., 2016), entropy weighted grey relation analysis (Chen et al., 2018), and fault tree analysis (Chen et al., 2020a). However, these studies have primarily focused on risk modeling and risk assessment, while limited studies were reported on the graded assessments of the societal risk of influencing factors. Therefore, quantitative evaluation of the societal risk levels of various accident factors will be emphasized in this paper.

Establishing SRAC is an essential step in risk assessment. SRAC considers the possibility of catastrophic accidents of major societal concern, intending to limit the risks from ships to society as a whole, as well as to local communities (*e.g.*, ports) that may be affected by ship activities (Vidmar and Perkovič, 2015; Yang et al., 2013). Many previous studies have focused on establishing the SRAC of fatal accidents of different research objects. For example, the IMO formed fatality SRAC for tankers, bulk and ore carriers, container ships, and passenger ro-ro ships in 2000 (IMO, 2000) and provided the fatality SRAC for the International Association of Classification Societies (IACS) general cargo ships in 2010 (IMO, 2010). Kaneko et al. (2015) presented a new method to establish SRAC and conducted empirical studies using fatal accident data from some ship types (*e.g.*, LPG tanker, chemical tanker) to validate the new method's effectiveness. Sun et al. (2018) proposed an approach to construct SRAC and undertake methodological empirical research using cruise ship and RoPax ship fatality data. Furthermore, accidents in other research fields, such as offshore oil and gas industry (Aven and Vinnem, 2005), dams (Li et al., 2015), gas industry (Zhang et al., 2015), pressure pipelines (Pei et al., 2018), and gas distribution pipelines (Gong et al., 2020) also only focused on fatality risk. To the best of our



(a) Fatalities



(b) Injuries

Fig. 5. Spatial distribution risk map for different initial events.

knowledge, only a few studies have examined and assessed the risk of injury accidents, particularly in shipping activities, which have raised IMO's attention reflected in the most recent edition of the FSA guidelines (IMO, 2018).

Many previous studies on maritime accidents have largely focused on risk modeling, risk assessment, factor classification, etc., while only a few studies have concentrated on the risk acceptance criteria of maritime accidents. Some SRAC for specific ship types (*e.g.*, cruise ships and crude oil tankers) have been established, but they are particularly rare for general cargo ship accidents on a global scale. In addition, most previous studies only conducted a preliminary analysis of the SRAC of maritime accidents, but the grading assessments of the societal risk levels of various influencing factors are even rare. Furthermore, little study has been reported in the literature regarding the SRAC of marine injury accidents that further compares the societal risk level differences of influencing factors of fatality and injury accidents.

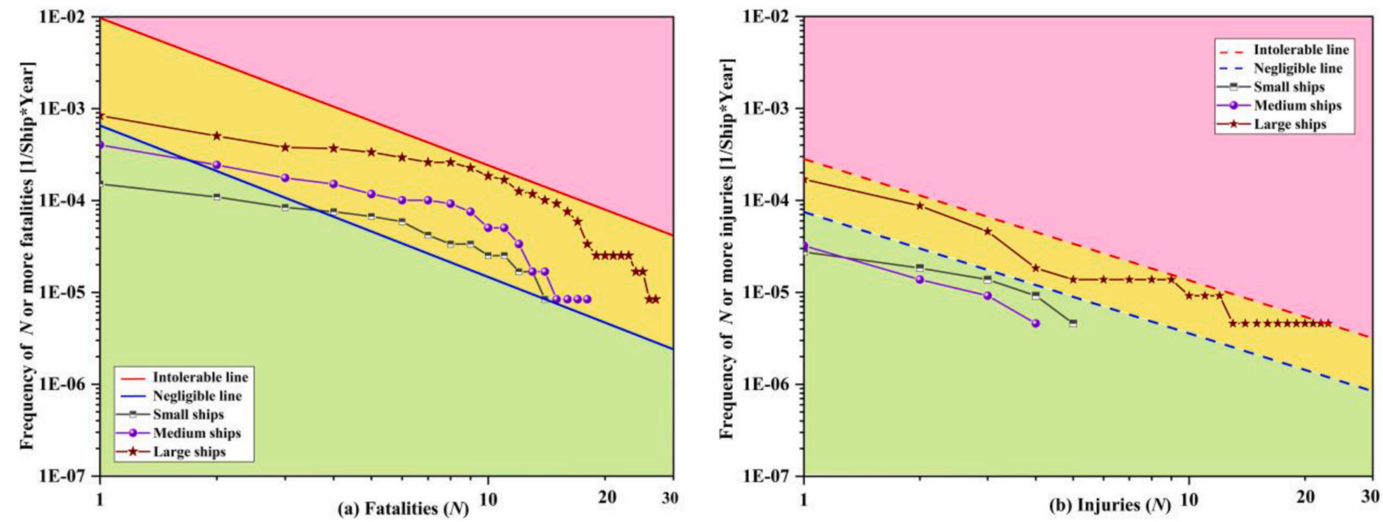


Fig. 6. Societal risk levels based on different ship sizes.

Therefore, considering the above research gaps, this paper aims to construct a set of SRAC for global general cargo ship fatality and injury accidents and comprehensively evaluates the fatality and injury societal risk levels of accident factors based on the latest general cargo ship accident data. This work also identifies the spatial risk distribution of fatality and injury accident factors.

3. Data description

The Global Integrated Shipping Information System (GISIS) database is an integrated marine information system issued by the IMO. Marine Casualties and Incidents (MCI) is one of the GISIS modules with two types of data on ship casualties. The first category of information consists of factual data gathered from various sources, and the second category is made up of more elaborate information based on reports received from IMO's casualty investigations, which may include full investigation reports to be analyzed by the IMO or reporting forms annexed to MSC-MEPC.3/Circ.3 (Huang et al., 2013). Previous research has revealed that some casualty databases may be non-public and non-disclosure (Kontovas and Psaraftis, 2009; Yang et al., 2013). Compared to other maritime data sources, the advantages of the GISIS-MCI database are its transparency, easy use, availability, and well-defined structure (Zhang et al., 2021b). Furthermore, GISIS-MIC is one of the databases certified by the IMO to carry out the FSA study, and its recorded maritime accident data is complete (IMO, 2017).

The data used for this study are the global general cargo ship accident data from the GISIS-MCI database, spanning from 2005 to 2019. Each accident element in this database includes the following items: (i) ship type; (ii) initial event; (iii) gross tonnage; (iv) classification society; (v) accident coordinates; (vi) accident date; and (vii) the number of fatalities and injuries. This paper investigates five general cargo ship types: deck cargo ship, general cargo ship, palletized cargo ship, passenger/general cargo ship, and refrigerated cargo ship. It is worth noting that the database records the number of crew members killed or missing in each general cargo ship accident. The chances of survival for missing crew members in maritime accidents are extremely low (Wang et al., 2022). As a result, the total number of fatalities is calculated by adding the killed and missing crews together.

General cargo ship accidents can be attributed to many complex factors involving all aspects of a particular type of ship, and the factors have different degrees of impact on fatality and injury. The risk factors of the general cargo ship accidents chosen for this study include the initial event, ship size, classification society, and geographical zone. The descriptive statistics of fatality and injury factors are shown in Table 1.

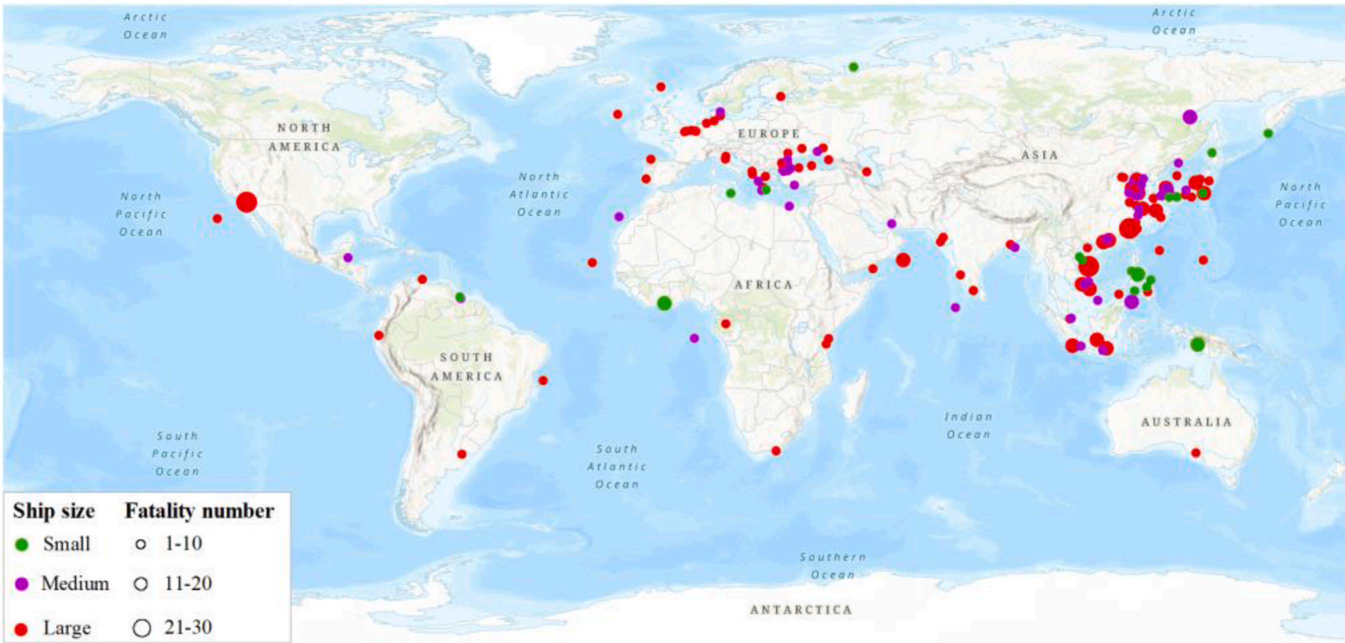
Capsizing, collision, contact, fire/explosion, hull failure, mechanical failure, missing, ship or equipment damage, stranding/grounding, and other events are the initial event types recorded in the GISIS-MCI database, accounting for 10.5%, 25.8%, 7.4%, 11.5%, 2.8%, 7.0%, 1.5%, 3.9%, 28.4%, and 1.3%, respectively. General cargo ship sizes are categorized into three types: small ships (GT $<$ 500), medium ships (500 $\leq$ GT $<$ 2,000), and large ships (2,000 $\leq$ GT), which account for 6.5%, 29.2%, and 64.3%, respectively. The classification society is divided into IACS and non-IACS, and 31.4% of the general cargo ships involved in the accident belong to IACS. It should be noted that all the ship accidents analyzed in this study are the initial events with clear causes but not the secondary accidents raised by the other types of accidents.

Based on the Equasis' method of geographical division, the world is separated into eleven zones (Equasis, 2019). Fig. 1 presents the spatial distribution of global general cargo ship accidents. Europe, the Mediterranean & Black Sea are responsible for 43.1% of all general cargo ship accidents worldwide. Accidents involving general cargo ships are also common in the waters near East & Southeast Asia, accounting for 35.8% of all accidents, and the other nine regions account for only 21.1% of the total.

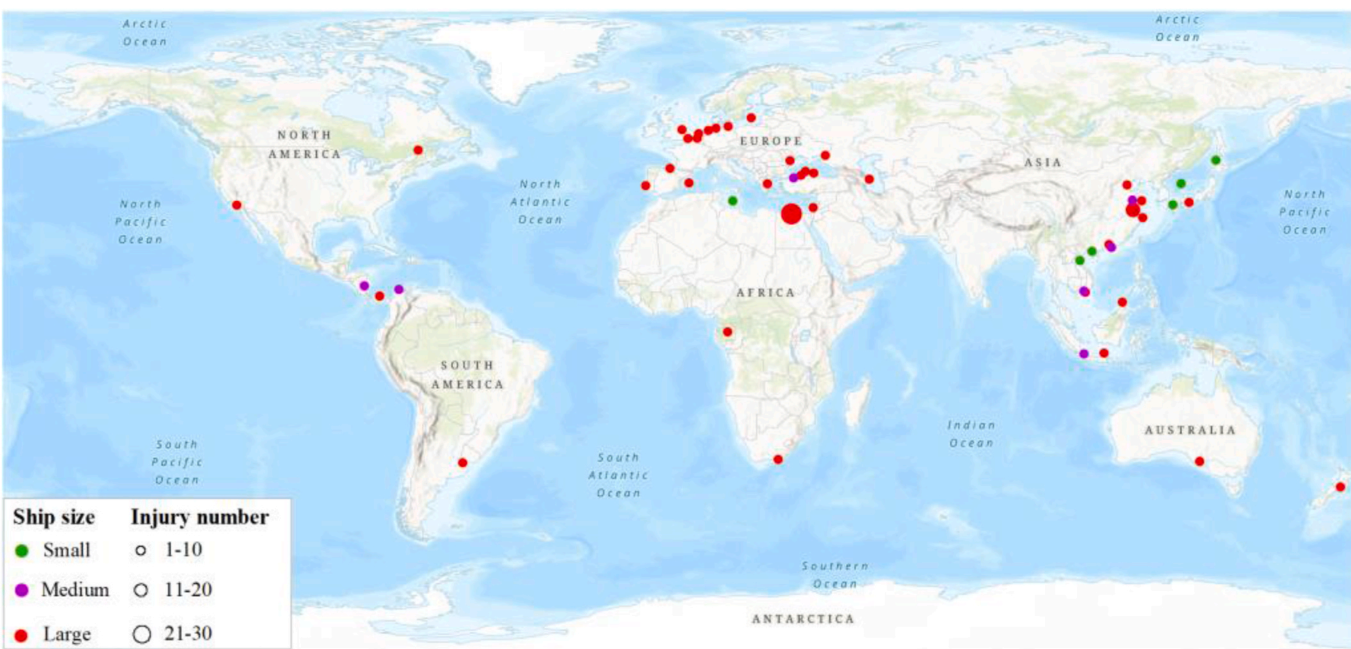
4. Methodology

The aggregated weighted risk (AWR), F–N curve, potential loss of lives (PLL), risk integral (RI), and societal risk index (SRI) are typical methodologies of the SRAC (Pei et al., 2018). The SRAC are usually determined by PLL or F–N curve in the maritime field. Compared to PLL, the F–N curve could clearly show the relationship between the cumulative frequency of an accident and the fatality number in a multidimensional diagram. Furthermore, the F–N curve allows for the assessment of the average number of fatalities and the risk of catastrophic accidents that kill many people at once. In sum, the F–N curve is a more efficient method of evaluating the societal risk of maritime accidents adopted in this study.

In this study, the F–N curve is constructed by estimating the number of fatalities/injuries for each hazard or accident scenario in turn. The overall frequency with which a given number of fatalities/injuries may be equaled or exceeded can be calculated and plotted in the form of a F–N curve using the estimated frequency of occurrence of each accident scenario. The F–N curve is, in fact, a continuous graph, with the ordinate representing the cumulative frequency distribution of N or more fatalities and the abscissa representing the consequence (N fatalities). Because of the wide range of variation in F and N, the F–N curve is usually depicted in the double logarithmic coordinate system (Evans and



(a) Fatalities



(b) Injuries

Fig. 7. Spatial distribution risk map for different ship sizes.

Verlander, 1997), and the theoretical expression is as follows:

$$F(n) = P(N \geq n) = \sum_{i=n}^{N_{\max}} f(i) \tag{1}$$

where $F(n)$ is the frequency of accidents involving n and more deaths per year; n is an integer constant; P is the frequency of accidents; $N_{\max}$ is the maximum possible number of deaths caused by an accident, and $f(i)$ is the frequency of accidents involving exactly i deaths per year.

The criterion lines are generally employed to determine whether the risk estimation output (societal risk described by F–N curves) has reached an acceptable level. Its theoretical expression can be expressed as follows:

$$F(N) \times N^{a} = k \tag{2}$$

The criterion line is essentially a straight line in the double

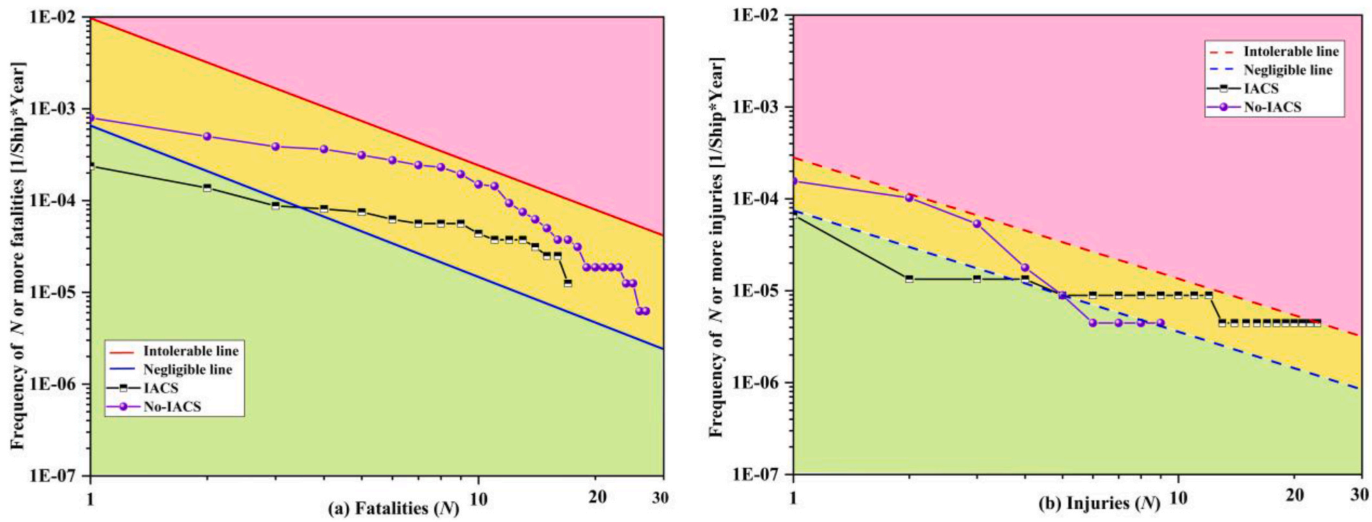


Fig. 8. Societal risk levels based on different classification societies.

logarithmic coordinate system, where a is the slope (also known as the risk aversion index) and k is the intercept (Gong et al., 2020; Pei et al., 2018). As a increases, the slope of the criterion line grows, resulting in more stringent criteria. Typically, $a = 1$ represents the risk neutrality, and $a = 2$ represents the risk aversion.

Taking the logarithm on both sides of Eq. (2), it yields,

$$\log_{10} F(N) + a\log_{10} N = \log_{10} k \tag{3}$$

5. Societal risk acceptance criteria (SRAC)

According to Eq. (1), $f(i)$ can be obtained by calculating the ratio between the number of ship accidents with exactly i fatalities/injuries and Ship*Year in the analyzed year. Then $F(n)$ can be calculated by the summation of $f(i)$ for these accidents with N or over N fatalities/injuries. Note that each Ship*Year is defined as one ship sailing for one year and retired or newly built ships within the analyzed year are then not considered in this study. Based on Eq. (3), we convert N and the annual average value of each F into $\log_{10} N$ and $\log_{10} F$, respectively, to perform the linear regression analysis. The results can be used to calculate a and k for the criterion F–N line. However, to avoid errors caused by abnormal data and improve data coordination, the hierarchical clustering method should be used prior to the linear regression to remove abnormal years (Gong et al., 2020).

A dendrogram is a tree diagram that is commonly used to depict the arrangement of clusters produced by hierarchical clustering (Kim et al., 2010). The clustering process can be analyzed and explained by observing the extension of the dendrogram. The dendrogram of the clustering analysis with the algorithm of between-groups average linkage is shown in Fig. 2.

In this study, the horizontal axis is considered as the distance between groups, and the vertical axis is the accident year. The difference between data groups is represented by the distance between groups; the larger the distance, the greater the difference between data groups will be (Zhang et al., 2015). For the fatalities dendrogram, it is discovered that 2010 and 2012 are the final years completing the merger from left to right in Fig. 2a, and they appear far apart from the others. If fifteen years of fatality data are separated into normal (black line) and abnormal (red line) groups from the right side of the dendrogram by a vertical line, the first separation point in 2010 and 2012 can be considered abnormal groups; that is, the fatality data for 2010 and 2012 do not show statistical characteristics that are common in other years. The reason for this could be that the number of fatalities in 2010 and 2012 is higher than in other years. From the left to right in Figs. 2b and 2002 (red line) is the last year completing the merger. Suppose fifteen years of injury data are divided into normal and abnormal groups. In that case, 2002 can be regarded as an abnormal group, possibly due to the higher number of injuries in 2002 than in other years. The remaining normal data of fatalities and injuries are analyzed by linear regression, respectively, and the results are shown in Table 2.

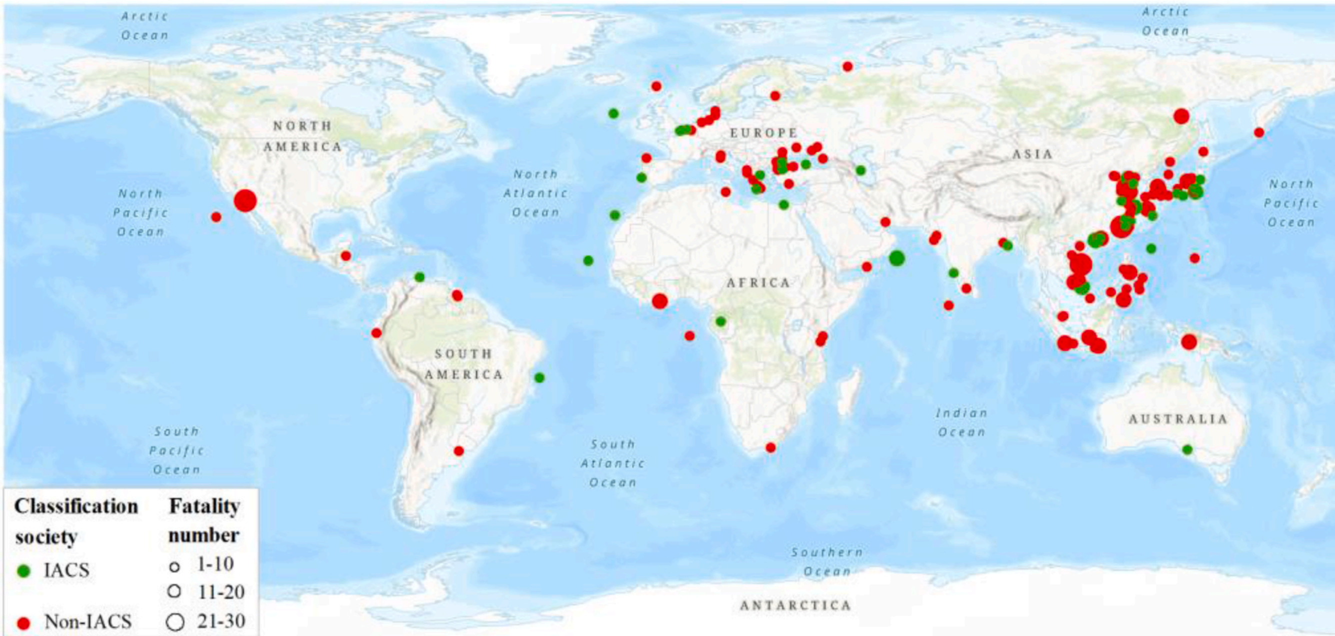
The R for the fatalities and injuries are 0.903 and 0.955, respectively, which have positive correlations with the imitative effect, indicating good fitting results of the two groups of data. In the F-test, the F-statistic (F-Sig.) significance probability of the fatalities and injuries are both 0.000, which is less than 0.05, indicating a significant linear relationship between $\log_{10} F$ and $\log_{10} N$. As a result, $\log_{10} F$ and $\log_{10} N$ are considered to be linearly related. The F–N lines of fatalities and injuries can be calculated by substituting a and k from the regression coefficients into Eq. (3). Table 3 shows the equations of the criterion lines of F–N diagram of fatalities and injuries.

Risk criteria that meet the requirements of different principles can be created by using different forms of risk expressions (Vanem, 2012). The commonly accepted principle in the maritime field is known as the ALARP principle (Kaneko et al., 2015). This principle states that there is a risk level that is “intolerable” above an upper bound (intolerable line). Risk cannot be justified in this region and must be reduced, regardless of cost. The principle also states that there is a “broadly acceptable” risk level below a lower bound (negligible line). Risk is negligible in this region, so no risk reduction is required. If the risk level is between the intolerable and negligible lines (ALARP region), risk should be reduced to meet economic responsibility (Kontovas and Psaraftis, 2009).

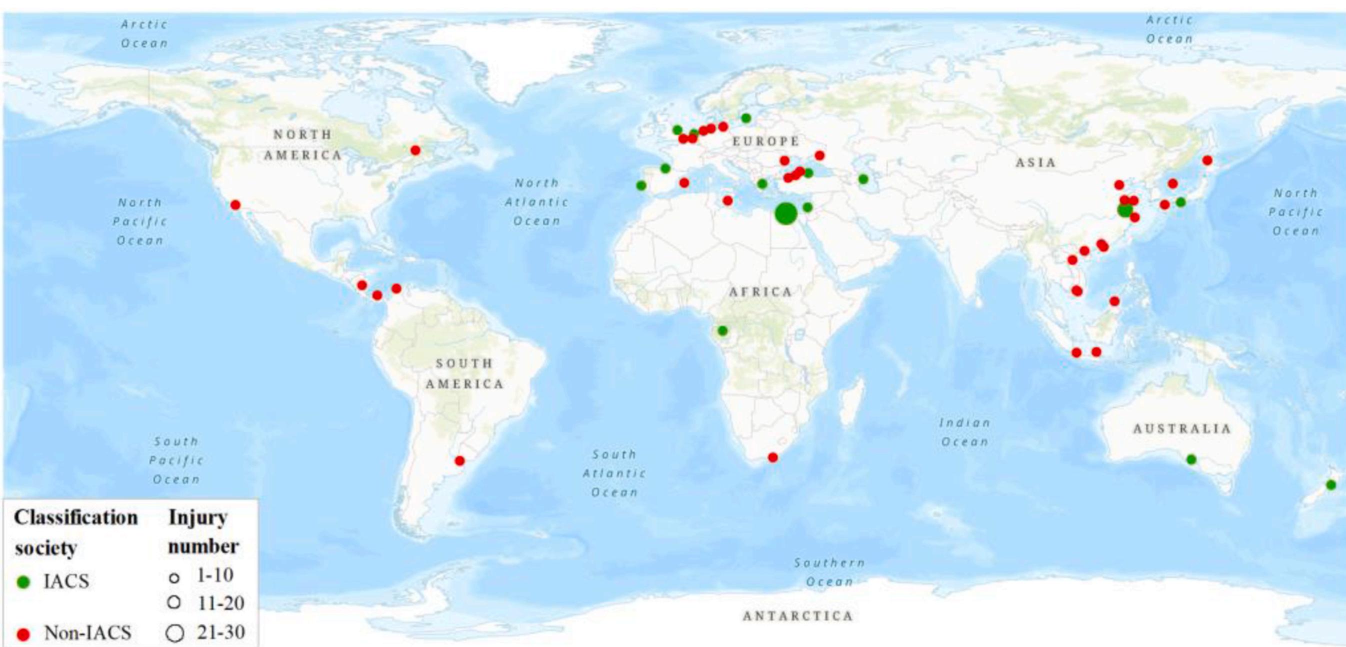
The predictive function of the established regression equation is used to achieve the final SRAC by combining the ALARP principle. Given the existence of errors between the estimated and actual values of $\log_{10} F$, interval estimation is required to determine the range of the actual value. According to statistical theory (Kutner et al., 2004), the prediction interval of the actual value of $\log_{10} F$ at a $1-\beta$ confidence level is,

$$\log_{10} F(N) \pm t_{\beta/2}(m-2)S_e\sqrt{1+\frac{1}{m}+\frac{(\log_{10} N-\overline{\log_{10} N})^2}{\sum_{i=1}^{m}(\log_{10}N_i-\overline{\log_{10} N})^2}} \tag{4}$$

where $\log_{10} F(N)$ is the estimated value obtained from Table 3; $t_{\beta/2}(m-2)$ is the critical value of t in the case of a t-distribution where the significance level is $\beta/2$ and the degree of freedom is $m-2$, which can be found in the t-critical value table; β is the significance level; m is the sample size, that is, the number of data points; S_e is the standard error of the estimate, which measures the relative deviation between the



(a) Fatalities



(b) Injuries

Fig. 9. Spatial distribution risk map for different classification societies.

actual value and its estimated value (Table 2); $\overline{\log_{10} N}$ is the average of $\log_{10} N$ s; and N_i is the N value of the i data point.

When the sample size is larger, formula (4) can be approximated as follows:

$$\log_{10} F(N) \pm t_{\beta/2}(\infty)S_e \tag{5}$$

where $t_{\beta/2}(\infty)S_e$ is a constant.

According to formula (5), for any $\log_{10} N$, the corresponding actual value $\log_{10} F$ always has a probability of $1-\beta$ falling within the above interval. Using the ALARP principle in conjunction with this statistical theory, the prediction interval of the actual value of $\log_{10}F$ is set at a 95% confidence level as the tolerable region of societal risk. The intolerable and negligible lines can then be determined using Table 3 and formula (5), and the results are shown in Table 4. Wherein, $t_{0.025}(\infty)$ is 1.960, and the S_e values for fatalities and injuries are 0.292024 and 0.150178

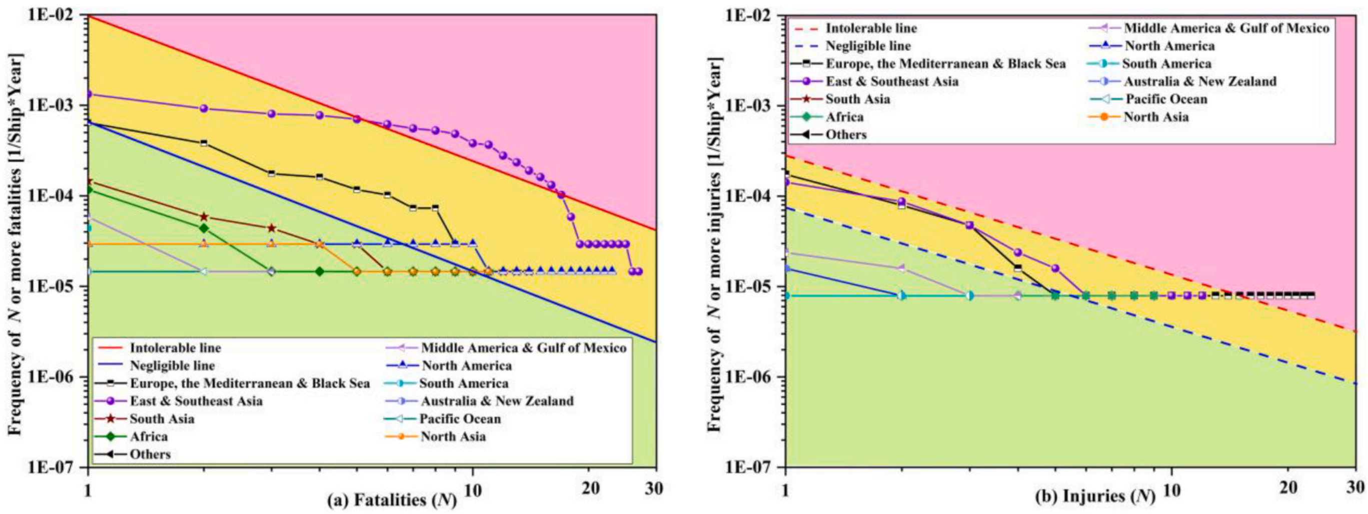


Fig. 10. Societal risk levels based on different geographical zones.

(see Table 2), respectively.

The SRAC for general cargo ship fatality and injury accidents are shown in Fig. 3. To better visualize the SRAC, the intolerable region, ALARP region, and broadly acceptable region are colored pink, yellow, and green, respectively.

6. Assessing the risk level of accident factors

6.1. Dependence on initial event

Fire/explosion and capsizing have the highest level of societal risk for fatality accidents, with a risk level in the intolerable region (see Fig. 4a). The risk curves of collision, contact, ship or equipment damage, mechanical failure, missing, and stranding/grounding are above the negligible line and below the intolerable line, suggesting that societal risk levels of these initial events are in the ALARP region. Hull failure poses relatively low risks, falling within the broadly acceptable region. Regarding injury accidents (see Fig. 4b), the risk curve for fire/explosion exceeds the intolerable line, indicating that the risk level is in the intolerable region. Collision, capsizing, and ship or equipment damage all have risk curves that exceed the intolerable line, which means that the risk levels are in the ALARP region. Other initial events' risk levels are broadly acceptable.

According to a comprehensive risk assessment of fatality and injury accidents, general cargo ships face the greatest risk of fire/explosion. Previous studies found that fire/explosion is strongly linked to the severity of crew injuries (Weng et al., 2016), and is also a major influencing factor in total-loss marine accidents worldwide (Chen et al., 2019). In fact, due to the limited reaction time, a large proportion of fires/explosion accidents, especially those involving small vessels, result in a low chance of survival for those trapped on the ship (Zhang et al., 2021a). Previous research has shown that human error, thermal reaction, electrical fault, and mechanical failures are the primary causes of fire/explosion accidents and that eliminating or controlling the ignition source and flammable and explosive materials on the ships are effective methods to reduce the frequency of fire/explosion accidents and the damage caused by accidents (Baalisampang et al., 2018). Furthermore, it is necessary to standardize dangerous goods management on ships, perform reasonable loading and unloading and safe transportation of hazardous goods in strict compliance with regulations, and improve crew awareness of fire prevention (Uğurlu, 2016).

The high risk of fatalities and injuries on general cargo ships is strongly related to capsizing, which is consistent with the findings of previous studies (Eliopoulou et al., 2016; Weng et al., 2016). Ships will capsize in most cases if a large-scale rolling motion occurs and the restoring moment is insufficient, and bad weather is always a factor in such accidents (Hu et al., 2019). One effective method for preventing capsizing is collecting meteorological information promptly and thoroughly considering the threat of adverse weather during the voyage (Allianz Global Corporate and Specialty, 2019). In addition, ship safety inspection should be strengthened to ensure that ships are in good condition (Wang et al., 2021).

Initial events (*e.g.*, collisions, ship or equipment damage) with societal risk levels in the ALARP region should be reduced to meet economic responsibility. The risk of other initial events is negligible and thus does not require risk reduction.

To better visualize the spatial distribution risk map of general cargo ship accidents, the accident consequences are divided into three levels: general accidents (1 $\leq$ fatality/injury $\leq$10), serious accidents (11 $\leq$ fatality/injury $\leq$20), and major accidents (21 $\leq$ fatality/injury $\leq$30). The spatial distribution risk map of different initial events is presented in Fig. 5. For those fatality accidents (see Fig. 5a), the general accidents involving capsizing, fire/explosion, and collision are more likely to occur in East & Southeast Asia, followed by the Eastern Mediterranean and the Black Sea. And East & Southeast Asia has the highest frequency of serious capsizing and fire/explosion accidents. In terms of injury accidents (see Fig. 5b), the Eastern Mediterranean and the Black Sea are high-risk areas for capsizing and fire/explosion, collision accidents are more common in East Asia, and the other types of initial events are widely dispersed.

6.2. Dependence on ship size

Fig. 6 presents the societal risk levels of different ship sizes. Specifically, the societal risk level of large general cargo ships is in the ALARP region in terms of both fatality and injury accidents. The societal risks of fatality accidents on small and medium-sized ships are all within the ALARP region, and the risks of injury accidents are broadly acceptable. Large general cargo ships face a higher level of risk in general, which may be due to large ships' poor maneuverability compared to those small ships, increasing the likelihood of accidents (Li et al., 2014).

Fig. 7 depicts the spatial distribution risk map of different ship sizes. Regarding fatalities (see Fig. 7a), the waters around the Philippines are high-risk for small general cargo ships. General accidents involving medium-sized ships are more likely to occur in East & Southeast Asia, the Eastern Mediterranean, and the Black Sea, where East Asia shows the highest proportion of serious accidents. Western Europe, Eastern Mediterranean, Black Sea, and East & Southeast Asia have the highest

Table 5
SRAC for different ship types.

Ship types	Time	Data source	Slope	The anchor points of the negligible line	The anchor points of the intolerable line
Tankers (IMO, 2000)	1978–1998	LMIS	1	(10, 2.00E-05)	(10, 2.00E-03)
Bulk and ore carriers, container ships (IMO, 2000)	1978–1998	LMIS	1	(10, 1.00E-05)	(10, 1.00E-03)
Passenger ro-ro ships (IMO, 2000)	1989–1998	LMIS	1	(10, 1.00E-04)	(10, 1.00E-02)
LNG tankers (Vanem et al., 2008)	1965–2005	Several sources	1	(10, 8.00E-06)	(10, 8.00E-04)
General cargo ships of IASC (IMO, 2010)	1997–2008	Lloyds Register Fairplay	1	(10, 1.00E-05)	(10, 1.00E-03)
Cruise ships (Vidmar and Perkovič, 2015)	2005–2014	EMSA and other reports	1	(10, 1.57E-04)	(10, 1.57E-02)
Crude oil tankers (Vidmar and Perkovič, 2018)	1980–2016	EMSA and other reports	1	(10, 1.60E-06)	(10, 1.60E-04)
Cruise ships (Sun et al., 2018)	2000–2012	FSA report	1	(10, 4.50E-05)	(10, 6.80E-03)
RoPax ships (Sun et al., 2018)	2000–2012	FSA report	1	(10, 2.10E-05)	(10, 9.90E-03)
Injury accidents of general cargo ships (This paper)	2005–2019	GISIS-MCI	1.319	(10, 3.50E-06)	(10, 1.36E-05)
Fatality accidents of general cargo ships (This paper)	2005–2019	GISIS-MCI	1.650	(10, 1.50E-05)	(10, 2.10E-04)

frequency of general accidents of large ships, and the majority of serious and major accidents are more likely to occur in East & Southeast Asia. Regarding injury accidents (see Fig. 7b), East & Southeast Asia records the highest number of small and medium-sized general cargo ships, and Western Europe is the high-risk area for large general cargo ships.

6.3. Dependence on classification society

Fig. 8 shows the societal risk levels of different classification societies. According to the figure, the societal risk levels of IACS and non-IACS general cargo ships are both in the ALARP region, with the non-IACS general cargo ships facing a higher fatality risk.

The spatial distribution risk map of different classification societies is shown in Fig. 9. For those IACS fatalities (see Fig. 9a), China's coastal waters record the highest number of serious accidents, and general accidents are more likely to occur in East Asia, the Eastern Mediterranean, and the Black Sea. East & Southeast Asia has the highest frequency of non-IACS general accidents, followed by Western Europe, Eastern Mediterranean, and the Black Sea, and East & Southeast Asia are hotspot areas of severe accidents. Regarding injury accidents (Fig. 9b), general IACS accidents are more likely to occur in Europe, and serious non-IACS severe accidents are more common in East & Southeast Asia and Western Europe.

6.4. Dependence on geographical zone

The societal risk levels of different geographical zones for general cargo ships are shown in Fig. 10. For fatality accidents (see Fig. 10a), the risk curve of East & Southeast Asia exceeds the intolerable line, indicating that the societal risk level is intolerable. Europe, the Mediterranean & Black Sea, South Asia, Africa, North America, and North Asia have risk curves that exceed the negligible line, implying that risks are in the ALARP region, where the risk levels from other areas are broadly acceptable. Regarding injury accidents (see Fig. 10b), Europe, the Mediterranean & Black Sea's risk curve exceeds the intolerable line, suggesting that the risk is in the intolerable region. In addition, the risk levels of East & Southeast Asia and South Asia are in the ALARP region, and risk levels in the other areas are broadly acceptable.

Overall, the societal risk levels of fatality accidents in East & Southeast Asia and injury accidents in Europe, the Mediterranean & Black Sea are highest. According to statistics (Sirimanne et al., 2020), Europe and East & Southeast Asia account for 29.9% and 24.4% of global general cargo trade, respectively, from 2005 to 2020, and high traffic density areas for cargo ships are located in these areas (Wu et al., 2016). In addition, with their advanced shipping businesses and dense shipping routes, the Mediterranean and the Black Sea are important water areas connecting southern European countries and Asia, Europe, and Africa (Wang et al., 2022). Furthermore, poor geographical conditions and adverse weather contribute to accidents in the waters surrounding Europe, the Mediterranean & Black Sea (Zhang et al., 2021b). It should be noted that North Asia accounts for only 0.4% of all general cargo ship accidents worldwide, and the societal risk level of fatality risk is relatively high (ALARP region). This could be because most accidents in this zone are fatality accidents caused by adverse weather or hazardous hydro-meteorological conditions (Xu et al., 2022).

Fig. 11 depicts the spatial distribution risk map of various geographical zones. Specifically, the maritime management department should pay attention to fatality accidents in East & Southeast Asia and injury accidents in Europe, the Mediterranean & Black Sea. Risk control activities should be implemented to reduce the societal risk levels in those two geographical zones to the ALARP risk region. Risk control options should be maintained in geographic zones (*e.g.*, South Asia) where the societal risk levels of fatality or injury accidents are in the ALARP region to keep the risk at this level. From an economic point of view, other geographic zones do not require special precautions.

7. Discussion

7.1. Different SRAC for maritime accidents

The slope and anchor point of the risk line are important parameters in describing the F–N curve, where the slope of the risk lines describes the preference for avoiding large accidents. And an anchor point is a fixed point with a corresponding pair of consequences (number of fatalities, *N*) and frequency (probability of accidents with *N* or more fatalities per year, *F*) as coordinates: (*N*, *F*). Table 5 shows the slope and anchor point of the SRAC for various ship types. The SRAC for injury accidents on general cargo ships are more stringent than that of fatality accidents, primarily because the number of fatalities recorded in the database is bigger than that of injuries. The anchor points of fatality

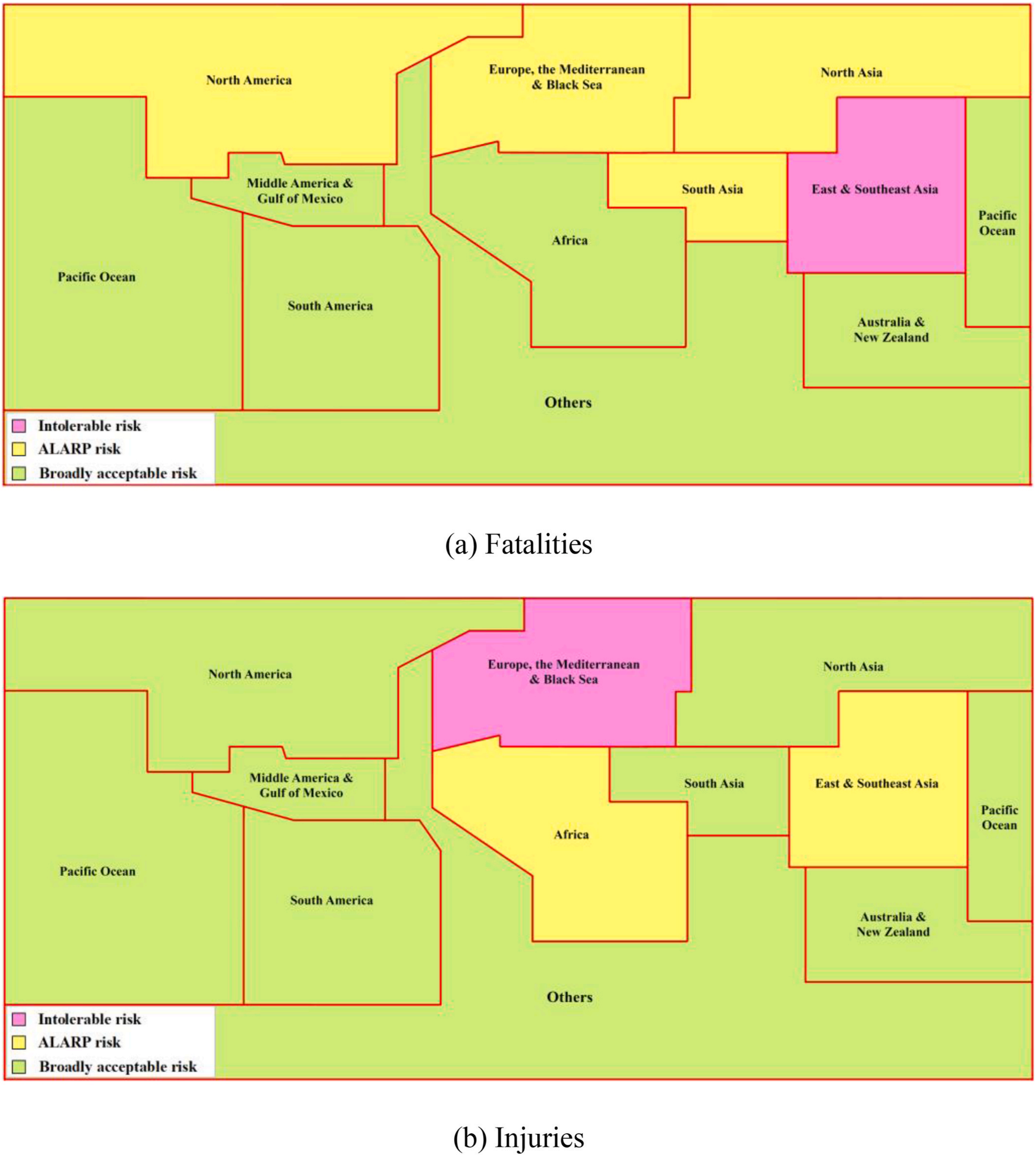


Fig. 11. Spatial distribution risk map for different geographical zones.

accidents established in this study are lower than those constructed in 2010 by the IMO for general cargo ships, indicating that the SRAC of this study are stricter, which is consistent with the fact that with improvements in technology, risk management, and ship navigation conditions, people's tolerable level of accident risk decreases (Eliopoulou et al., 2016). In addition, the anchor points determined in this study are one to two orders of magnitude lower than passenger ships (*i.e.*, passenger ro-ro ships, cruise ships, RoPax ships), suggesting that passenger ships face higher societal risks, which may be explained by the fact that passenger ships carry a large number of peoples (even more than 1,000), and accidents frequently result in more casualties (Sun et al., 2018). Furthermore, unlike conventional research that only focuses on the fatality risk, this study establishes SRAC for general cargo ship fatality and injury accidents, which allows for a more comprehensive understanding of the risks of general cargo ships.

Given that North Asia accounts for only a few general cargo ship

Table 6
Interpretation of uncertainty and sensitivity ratings for uncertainty and sensitivity analysis.

Aspect	Rating	Interpretation
Uncertainty	Low	The assumptions made are reasonable; Much reliable data is available; The phenomena involved are well understood, models are known to give predictions with the required accuracy.
	Moderate	Conditions between those characterizing low and high uncertainty.
	High	Conditions opposite to those characterizing low uncertainty.
Sensitivity	Low	Large changes in base values needed to bring about altered conclusions.
	Moderate	Relatively large changes in base values needed to bring about altered conclusions.
	High	Relatively small changes in base values needed to bring about altered conclusions.

accidents worldwide, the societal risk level of fatality risk is relatively high (see Fig. 11a). In particular, the melting of Arctic Sea ice and the advancement of maritime technology have enabled regular voyages in the Arctic waters in recent years, causing maritime industries and academics to pay considerable attention to the risk analysis of ships sailing in the Arctic Sea (Fu et al., 2018; Xu et al., 2022). The establishment of SRAC is an important part of risk analysis and assessment. The Arctic route (*e.g.*, Arctic Ocean seasonally covered with sea ice) characteristics should be fully considered when establishing the SRAC for ice-going ships in the Arctic. Additionally, when conducting risk assessments, it is necessary to consider the different seasons, routes (*e.g.*, Northeast Passage and Northwest Passage routes), weather conditions, ice conditions, navigation with icebreaker assistance conditions, etc.

7.2. Validation

The F–N curve with the slope of 1 proposed by IMO is considered appropriate in the shipping industry and has been widely applied to various ship types (*e.g.*, tankers, container ships, cruise ships). However, the current research suggests that the slope of the F–N curve is more specific and more suitable for one industry (Gong et al., 2020). In contrast to other studies that subjectively define the slope of the risk line as 1, the more specific slopes of general cargo ship fatality and injury accidents established in this study are 1.650 and 1.319, respectively, and the slope values are within a reasonable range of 1–2 (see Table 5). In addition, the F–N curves of fatality and injury accidents are distributed between the negligible and intolerable lines (see Fig. 3), which also indicate that the SRAC of general cargo ships established in this study are reasonable. All above verify the reliability of the method used in this study. That also says that the linear regression analysis matches the expression of the F–N curve, and the predictive function of the regression equation can also be effectively combined with the ALARP principle.

7.3. Discussion on uncertainties and sensitivities

SRAC for general cargo ship fatality and injury accidents are investigated using data from the IMO's GISIS-MCI database. The uncertainties and sensitivities of data inaccuracies, model assumptions, and approach or modeling procedures that may affect the results are considered before concluding the paper. Currently, numerous uncertainty assessment methodologies have been proposed (Goerlandt et al., 2017; Liu et al., 2020; Zhang et al., 2019b, 2022). The method suggested by Flage and Aven (2009) is used in this study. Table 6 presents a brief justification of the rating associated with the qualitative for evaluating the uncertainty and sensitivity. The evaluation could serve as a guide for additional research and methodological refinement.

Table 7 displays the uncertainty and sensitivity ratings for the various inputs and methods in the paper, showing that the data sources and data processing methods are generally free of uncertainty. Sensitivities are also expected to be relatively low. In addition, the uncertainties regarding the hierarchical clustering method are moderate. This is addressed further in Section 8, where future work directions are discussed.

Table 7
The uncertainty and sensitivity assessment for SRAC.

Model element	Uncertainty	Sensitivity	Justification
GISIS-MCI data	Low	Low	•When compared to other maritime accident databases, the strength of GISIS-MCI data is its transparency, ease of use, availability, and well-defined structure (Zhang et al., 2021b). However, some of the accident information is left blank or is filled out incorrectly according to the GISIS-MCI format. Therefore, all data (ship type, initial event, gross tonnage, classification society, accident coordinates, accident date, and the number of fatalities and injuries) are checked and corrected to create a more reliable dataset. Because the amount of missing or incorrect data is small, the impact is expected to be minimal.
Selected accident factors	Low	Low	•The four accident factors selected include all the data needed to calculate the results.
Assumptions	Low	Low	•Given that the chances of survival for missing crew members in maritime accidents are extremely low. In Section 3, the total number of fatalities is calculated by adding the crews who died and those who went missing. However, due to the extremely small number of missing crew members recorded in the database, the effects of these potentially unreliable data instances are expected to be rather low. •Ship*Year is defined as one ship sailing for one year and retired or newly-built ships during the analyzed year are not taken into account in Section 5. Therefore, the supposed statistics on the Ship*Year may contain some inaccuracies.
Hierarchical clustering method	Moderate	Low	•Before the linear regression, the hierarchical clustering method is used to remove abnormal years to avoid errors caused by abnormal data (*e.g.*, underreported maritime accidents) and improve data coordination. Following the removal of abnormal data, the remaining normal data of fatalities and injuries is analyzed using linear regression in Section 5. The removal of abnormal years may affect the results. The uncertainty associated with the hierarchical clustering method can be considered moderate due to the large dataset and good fitting results of the linear regression analysis.

8. Conclusions and future works

In this study, the SRAC of fatality and injury accidents are constructed using the statistics of global general cargo ship accidents in the last 15 years. In addition, the societal risk levels of fatality and injury for various accident factors are comprehensively assessed, and the spatial distribution risk maps of fatality and injury factors are visualized. Our results show that the slopes of the SRAC for fatality and injury accidents are 1.650 and 1.319, respectively. For fatality accidents, the anchor points of the negligible and intolerable lines are (10, 1.50E-05) and (10, 2.10E-04), and for injury accidents, they are (10, 3.50E-06) and (10, 1.36E-05). The SRAC for injury accidents are more stringent than that of fatality accidents. The SRAC for general cargo ship fatality accidents established in this paper are stricter than that formulated by IMO in 2000. The societal risk levels of fire/explosion and capsizing are intolerable, and other initial events face a low risk within the ALARP or broadly acceptable region. Large general cargo ships have a higher societal risk level than small and medium ships. The societal risk levels of IACS and non-IACS ships are in the ALARP region, and non-IACS ships are at a higher risk than IACS ships. The societal risk levels of fatality accidents in East & Southeast Asia and injury accidents in Europe, the Mediterranean & Black Sea are intolerable, and risk levels in other geographic regions are lower. The research findings presents a new ruler to examine the current risk state of general cargo ship accidents and evaluate the effectiveness of actions taking by maritime safety authorities and ship owners/operators.

This study is also probably limited at least by three aspects. Firstly, the risk acceptance criteria for property loss and marine pollution have not been established due to data limitations. Secondly, the reliability of risk and accident analysis results may be impacted by missing (*e.g.*, underreported maritime accidents) or abnormal data, and more effective methods to reduce the errors and uncertainties caused by data should be developed. Thirdly, by taking into account the ship routes (*e.g.*, Arctic routes), ship ages, ship flags, and traffic levels, the risk factors of ships can be further subdivided, allowing for a more comprehensive risk assessment in the future.

CRediT authorship contribution statement

Jinhui Wang: Formal analysis, Methodology, Validation, Writing - original draft. **Yu Zhou:** Software, Formal analysis, Investigation, Visualization, Writing – original draft. **Shaogang Zhang:** Methodology, Supervision, Resources. **Lei Zhuang:** Validation, Investigation. **Long Shi:** Formal analysis. **Jihong Chen:** Conceptualization, Methodology, Writing – original draft, Validation, Project administration, Funding acquisition, Supervision. **Daoxian Hu:** Resources, Project administration, Supervision.

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

The data that has been used is confidential.

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