A Probabilistic Safety Assessment Framework for Arctic Marine Traffic Using the Evidential Reasoning Approach

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Abstract

The global warming has made Arctic marine traffic possible, but the harsh navigation environment threatens its safety and restrains its development. It is necessary to evaluate the safety of Arctic marine traffic environment. The evidential reasoning approach is used to establish a new hierarchical model for the safety evaluation due to its advantages such as being able to deal with uncertainty caused by ignorance or lack of knowledge. The model is based on objective environmental data of safety gathered from the Arctic voyage of a general cargo vessel 'Tian You' and subjective judgements collected from domain experts. The safety evaluation results show that the locations in East Siberian and Laptev Sea have a generally safer environment for marine traffic than the one in Kara Sea. The proposed model validated by sensitivity analysis provides an informative and rigorous basis for decision making of Arctic marine traffic.

Keywords: Safety evaluation; Arctic marine traffic; Expert judgements; Evidential reasoning approach; Multiple criteria decision making.

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1. Introduction

Recently, the global warming has led to the melting of the Arctic sea ice, and the Arctic waters hence has become more accessible for commercial and industrial development (Verny and Grigentin, 2009; Ho, 2010). As a result of the opening Arctic waters, the frontier of natural resource exploitation can be significantly pushed further north (Fu et al., 2016), and the voyage distances between east Asia and Europe can be dramatically reduced (Suárez de la Fuente et al., 2018). The Arctic has been estimated to contain a vast reserve of natural gas, massive deposits of oil, and other minerals (Lee et al., 2015). Continued efforts have been made by different countries to unearth the potential for the Arctic natural resources, despite the difficulties for exploiting these resources (Afenyo et al., 2019). In the U.S. Arctic waters, Prudhoe Bay Oil Field, the largest oil field in North America, discovered in 1968, is operated by BP in partnership with ExxonMobil and ConocoPhillips Alaska (BP, 2010). In addition, Royal Dutch Shell was granted licenses for the exploration and drilling in Chukchi Sea (Macalister, 2015). In the Kara sea, with the permission of Russia government, Rosneft and ExxonMobil jointly discovered oil and launched commercial production (Henderson and Loe, 2014), although ExxonMobil quit due to the U.S. sanction to Russia. Aside from the U.S. and Russia, China, as a 'near-Arctic state' shows growing interests in the Arctic shipping voyage, and tries to extend the Belt and Road Initiative (BRI) to the Arctic by using the 'Polar Silk Road' which connects China and Europa through the Arctic Ocean (Lasserre et al., 2018). Since the successful voyage of multipurpose vessel 'Yongsheng' in 2013, the number of Chinese cargo vessels applying for navigation via the Northern Sea Route (NSR) of the Arctic waters has kept increasing from 8 in 2013, 1 in 2015, 11 in 2016 to 15 in 2017 (Lasserre et al., 2018). Approximately 1 million tons of cargo has been shipped from China via the NSR, and it has been estimated that about 1% of Chinese freight will have been transited through the NSR by 2020 (Lasserre et al., 2018). By using the policy of 'Polar Silk Road', China will be more active in the Arctic, which may lead to the rise of level for shipping traffic via the Arctic waters.

The Arctic waters are hence attractive for exploitation of natural resource and intercontinental shipping transits (Lee et al., 2015), which can lead to an increase for the number of marine traffic. However, the number of marine traffic in the Arctic waters only accounts for a small proportion of the total international shipping transits, and there is insufficient response capacity for emergencies (Fu et al., 2018). One of the reasons contributing to the status quo is that the safety environment of the Arctic waters has long been considered as ‘harsh’. This is reflected by sea ice, drifting icebergs, extremely low temperatures, insufficient and inaccurate hydrographic information, fast-changing severe weather conditions, etc., (Fu et al., 2016; Meng et al., 2017), which threaten the safety of seafarers and ships (Arctic Council, 2009). With the increased size and number of ships (Toffoli et al., 2005), shipping accidents are more likely to occur in the Arctic waters (Borgerson, 2008). It is confirmed by studies that the increased traffic of oil tankers in Barents Sea will lead to a considerable number of accidents, if no further safety measures are adopted (Norwegian Ministry of the Environment, 2012). Thus, the safety of the marine traffic in the Arctic waters has become of significant interest (Fu et al., 2016). It is necessary to perform safety evaluation to analyse safety risk for marine traffic in the Arctic sea.

A considerable number of studies have been conducted to investigate the safety risk related to the marine traffic in the Arctic waters. At the 94th Maritime Safety Committee meeting, the ‘International Code for Ships Operating in Polar Waters (Polar Code)’ was adopted by the International Maritime Organization (IMO) (Jensen, 2016). The polar code emphasizes a comprehensive list of hazards for marine activities in the Arctic waters, but it has made few efforts to illustrate the risk influencing factors (RIFs) for individual operations, or the modelling techniques for safety assessment (Fu et al., 2018; Jensen, 2016). Regarding the RIFs for the marine traffic, a group of accidental events and processes are identified to contribute to ship accidents (Yang et al., 2013b). A structural equation modelling method is used for the investigation of the interdependence between the RIFs in the marine transportation system for the Arctic waters (Fu et al., 2015). Safe marine traffic in the Arctic waters can be influenced by different environmental conditions, human factors, navigation aids, the vessel itself, and other vessels (Thompson, 2004). It has been found by Zhang et al., (2019) that ship speed and ice concentration are the major environmental factors of performance of ships navigating in the Arctic waters. In addition, the risk influencing factors may also involve ice condition, low temperature, a lack of seamarks, remoteness from populated areas, and the increased instability of equipment operations caused by the effects of high latitudes (Fu et al., 2015; Khan et al., 2014; Kum and Sahin, 2015). Visibility and human error are identified as remarkable contributors to ship collisions (Merrick et al., 2000; Van Dorp et al., 2001; Macrae, 2009; Zhang and Thai, 2016). Besides, significant human contributors to marine traffic also involve physical and mental fatigue, scanty knowledge for shipping system, inferior communication capability, etc., (Talley, 2002; Dhillon, 2007). With respect to the modelling techniques for safety assessment, Khan et al. (2014) applied the method of Bayesian network to propose a framework for the transportation risk analysis in the Arctic waters. A method of fuzzy fault tree is proposed by Kum and Sahin (2015), which considers a group of causal risk factors about human and management in reference to the accidents of collision and grounding in the Arctic waters. Fu et al. (2016) used Bayesian networks models to predict the probabilities of ships getting stuck in the NSR.

It is clear that among the safety risk studies associated with the marine traffic in the Arctic waters, the major modelling techniques are fuzzy logic and Bayesian networks. It is worth noting that fuzzy logic is difficult to manage the uncertainty caused by incompleteness or ignorance (Yang et al., 2006), despite its distinguished features in information fusion (Yang and Wang, 2015). Bayesian networks have the merits of probabilistic inference based on powerful algorithms (Kong et al., 2015a). Nevertheless, the complexity of Bayesian networks increases in an exponential way with the increase of the number of parameters for the networks (Kong et al., 2015a). They also require too much information about prior distributions, which heavily depends on the sampling method of data collection (Kong et al., 2015; Yang et al., 2019). In addition, probability completeness is required in Bayesian inference (Yang et al., 2019). The unavailability of statistical data can be complemented by subjective data (Yang et al., 2019). Although subjective probabilities can be generated by experts, it comes with problems such as consensus, accuracy, and completeness of judgements (Yang et al., 2019). Besides, the interdependence between RIFs has not been studied in depth in the models for the marine traffic in the Arctic waters (Fu et al., 2016).

The evidential reasoning (ER) approach is developed based on the Dempster-Shafer (D-S) theory of evidence (Dempster, 1968; Shafer, 1976). The ER approach comes up with a unique reasoning-based process for merging distributed assessments

(Yang et al., 2009), which has been used in a wide range of areas, e.g., motorcycle evaluation (Yang and Singh, 1994a), design (Yang and Xu, 1998), environment impact assessment (Wang et al., 2006), bridge condition assessment (Wang and Elhag, 2008), product assessment (Chin et al., 2009), nuclear waste repository assessment (Xu, 2009), weapon system capability assessment (Jiang et al., 2011), medical quality assessment (Kong et al., 2015b) and navigational risk assessment of inland waterway transportation systems (Zhang et al., 2016). It has the merits of handling both objective indicators and subjective evaluations under uncertainty, e.g., incompleteness and vagueness (Kong et al., 2015a). By employing the concept of degree of belief, the synthesizing capability of the ER approach for partial degrees of belief has expanded the application scope of the conventional probabilistic theory, especially in profiling and dealing with uncertain information such as ignorance and incompleteness (Yang et al., 2008). In contrast to fuzzy logic, the linguistic terms used in the ER approach can be distinctive, indicating that there are no overlaps between the meanings of consecutive linguistic terms (Yang et al., 2006), whilst the overlap of linguistic terms can be modelled by the subsets of distinctive linguistic terms. Furthermore, fuzzy logic can only be applied to manage the uncertainty caused by vagueness and fuzziness, while the ER approach can be used to deal with ignorance or incompleteness (Yang et al., 2013a). In the safety evaluation of Arctic marine traffic environment, there are uncertainties caused by factors such as insufficient information, knowledge, and experience, incomplete understanding of system, and lack of confidence in judgments. In addition, both quantitative and qualitative inputs are aggregated in the safety evaluation model. For these reasons, the ER approach is used to evaluate the overall safety state of the environment for the marine traffic in the Arctic waters based on subjective qualitative judgement and objective quantitative indicators in this paper. A pragmatic method is also applied to transform quantitative indicators to qualitative grades for assessment with a belief structure. The major contributions of this paper are summarised as follows.

(1). The ER approach is used to propose a new model for the safety evaluation of the Arctic marine traffic environment, which merges subjective and objective environmental factors of safety. In the evaluation process of subjective factors, we consider the experts' uncertainty caused by incomplete information, partial understanding, etc. The distributed assessments and utility values generated by the approach facilitate the comparison of safety level of different vessel locations in the Arctic waters.

(2). Environmental data related to safety used in this study were collected by the first author of this paper from navigation records during the Arctic voyage of the general cargo vessel 'Tian You'. The qualitative judgements were collected from questionnaires distributed to domain experts. All of this first-hand material about safety is authentic and reliable, which reflects the real safety environment of the Arctic navigation. The rationality and feasibility of the proposed model in this study have been validated by the sensitivity analysis focused on the weights of environmental factors in the criteria level of the proposed model.

(3). A systematic review is conducted for the environmental factors of safety in the criteria and sub-criteria levels of the proposed model, which provides a detailed description of the Arctic navigation environment from the perspectives of hydrometeorology, channel, traffic regulation, and navigation infrastructure.

The remaining part of this paper is organized as follows. Section 2 is mainly focused on data and the safety factors of the environmental evaluation for the Arctic marine traffic. Section 3 provides a brief introduction to the ER approach. In Section 4, a numerical example is used to illustrate the detailed process for data input, weight generation, data aggregation, and sensitivity analysis, which are all based on the ER approach. Section 5 presents the results of environmental evaluation and sensitivity analysis. The major contributions, limitations, and the potential research direction of this study are summarised in Section 6.

2. Data and environmental factors

2.1. Data

In the period from 26th August to 20th September in 2019, for the purpose of data collection, the first author of this paper had taken the general cargo vessel 'Tian You' operated by COSCO Shipping Specialized from Shanghai, China to Hamburg, Germany, which sailed through the Northeast Passage (NEP). The vessel 'Tian You', which has a length of 190 m, a beam of 28 m, a draught of 6.9 m, and a deadweight of 37559 t, is classified as CCS Ice Class B1 equivalent to LR Ice Class 1A ("Vessel details for: TIAN YOU", 2019). During the NEP voyage of 'Tian You', the author collected quantitative data about the hydrometeorological environmental factors (including sea ice concentration and thickness) for the navigation of 'Tian You' in the Arctic waters from deck log, ship performance recorder, electronic charts, sea ice monitoring system, etc. Qualitative judgements on other environmental factors were collected from questionnaires which were distributed to the domain experts such as the officers of 'Tian You', researchers focusing on the Arctic marine traffic, the administration of shipping companies, and the management of classification societies (e.g., China Classification Societies (CCS), Lloyd's Register). The information collected from the Northern Sea Route Administration of Russia, the National Marine Environmental Forecasting Center of China, etc., also provide a reference for this study.

2.2. Environmental factors of safety

Based on the relevant literatures and the extensive discussions with domain experts, 4 aspects of environmental factors of safety for the Arctic marine traffic are considered in this study, and they are hydrometeorology, channel, traffic regulation, and navigation infrastructure. The following part provides a brief introduction to these factors.

2.2.1. Hydrometeorology

The hydrometeorological factors identified in this study include wind and wave, visibility, sea ice concentration, and sea ice thickness. Wind is related to vessel operations (Montewka et al., 2013; Goerlandt et al., 2017). In summer which is appropriate for Arctic navigation, most parts of Russian Arctic are dominated by northern and eastern winds (Przybylak, 2013). Due to the high atmospheric pressure and high anticyclonic activity, the wind speed of whole Arctic Ocean is generally between 4 and 6 m/s (Przybylak, 2013). Ocean sea waves including sea and swell are caused by the winds which blows a distance for a period of time (Thomson and Rogers, 2014). A recent study shows that there is a positive correlation between wind speed and wave height in the ice-free Arctic waters (Waseda et al., 2018). In mid-September 2012, waves of 5 m high recorded in Arctic open water were generated by high winds (Thomson and Rogers, 2014). Wind can be empirically measured by the Beaufort scale which relates wind speed to wave height, and sea and land conditions (“Beaufort wind force scale - Met Office,” n.d.; “The Beaufort Scale - Royal Meteorological Society,” n.d.). For example, if the wind speed is between 5.5 and 7.9 m/s, the wind is classified as ‘Beaufort force 4’ indicating moderate breeze, and the relevant description for sea conditions is that small waves become longer and white horses are fairly frequent (“Beaufort wind force scale - Met Office,” n.d.; “The Beaufort Scale - Royal Meteorological Society,” n.d.). In the NSR area, visibility can be adversely influenced by fogs, blowing snow, etc., (American Bureau of Shipping, 2014). In this study, visibility is measured by the visibility level which is defined in the ‘International Comprehensive Ocean-Atmosphere Data Set (ICOADS)’ (Shan et al., 2019). The classification rule of visibility level (Shan et al., 2019) is given in Table 1.

Table 1

Classification rule of visibility level

Visibility level	1	2	3	4	5	6	7	8	9	10
Visibility distance (km)	≤ 0.05	0.05-0.2	0.2-0.5	0.5-1	1-2	2-4	4-10	10-20	20-50	≥ 50

Sea ice is a critical feature for Arctic marine traffic (Montewka et al., 2013; Fu et al., 2015; Kum and Sahin, 2015). The Arctic Ocean and part of peripheral seas are covered by sea ice during winter, while sea ice pulls back to the Arctic Ocean during summer (Walsh, 2008). Sea ice concentration and thickness are significant contributors to ice conditions (Montewka et al., 2013; Fu et al., 2015; Kum and Sahin, 2015). In this study, the ice data (those of sea ice concentration and thickness) were acquired based on the sea ice monitoring system installed on ‘Tian You’, which was developed by a research group focusing on the study of sea ice in a technology university. Based on the video images of ice (recorded by the monitoring system), the sea ice concentration and thickness of a specific sea area were calculated by the monitoring system using image segmentation and analysis techniques, and the projection principle, respectively.

Sea ice concentration is defined as a percentage of the ice-covered water area related to the entire observed water area, which ranges from 0% to 100% (Martin, 2007; Pastusiak, 2016). If the sea ice concentration ranges between 0% and 15%, the vessel can sail without obstructions (Canadian Ice Service, 2005; Pastusiak, 2016). For the Arctic sea ice thickness, the mean value of the period between 2003 and 2007 is about 1.43 m (Kwok and Rothrock, 2009). Broadly speaking, the larger the sea ice concentration and thickness are, the more difficult the vessels sail through a given leg of a sea route (Pastusiak, 2016). Moreover, changes of clouds may have an impact on the sea ice extent and thickness, and changes of sea ice can impart changes to cover of cloud (Eastman and Warren, 2010). Various types of clouds may have various influences on sea ice (Eastman and Warren, 2010). Air temperature is the most important and hence most often studied climatological factor for the Arctic (Przybylak, 2013). The mean air temperatures of winter in the central Arctic Ocean generally range from -30℃ to -33℃ (Serreze et al., 2005). In contrast, due to the melting sea ice, the mean air temperatures of July tend to hover around the freezing point (Serreze et al., 2005). Sensitivity experiments have illustrated that there is a robust relationship between air temperature and sea ice (Semenov and Bengtsson, 2003).

2.2.2. Channel

The physical environment of the northern coast of the Eurasian landmass is uniquely challenging to the technologies and systems of the Arctic marine traffic, which is generally featured by shallow water (Arctic Council, 2009). The average depths of Chukchi and East Siberian seas are 88 m and 58 m respectively, which are fairly shallow for marine traffic (Arctic Council, 2009). The Laptev Sea has an average depth of 578 m, but 66 percent of its coastal area has a depth of 100 m or less (Arctic Council, 2009). The average depth of Kara Sea is 90 m, and the southeastern coastal area of Barents Sea is in depths between 10 m and 100 m, and its northwestern area has depths between 200 m and 300 m (Arctic Council, 2009).

There are several narrow straits indicating significant constraints to the navigation through NSR (Arctic Council, 2009). They are Yugorskiy Shar Strait, Kara Gate, Vilkitskiy Strait, Dmitry Laptev Strait, and Sannikov Strait (Arctic Council, 2009), which are briefly introduced in Table 2.

Table 2

Brief introduction to the NSR straits

Name of strait	Length (nmi)	Width (nmi)	Depth (m)
Yugorskiy Shar Strait	21	6	13-30
Kara Gate	18	14	21 (minimum depth)
Vilkitskiy Strait	60	30	100-200
Shokalskiy Strait	80	10	37 (minimum depth)
Dmitry Laptev Strait	63	30	12-15
Sannikov Strait	160	16	13
Long Strait	120 (southern route) and 160 (northern route)	75	20 m (minimum depth for southern route) and 33 m (minimum depth for northern route)

Source: Arctic Council, 2009; Pastusiak, 2016.

2.2.3. Traffic regulation

In 2014, the International Maritime Organization (IMO) adopted an international regime - the International Code for Ships Operating in Polar Waters (Polar Code) (Mathiesen, 2014), which came into effect on 1st January 2017 (Deggim, 2018). It was developed in consideration of the International Convention for the Safety of Life at Sea (SOLAS) and the International Convention for the Prevention of Pollution from Ships

(MARPOL) (Deggim, 2018). It was proposed to protect vessels, seafarers and passengers in the harsh and vulnerable environment of the Arctic and Antarctic waters, and meanwhile it preserves environment (Deggim, 2018). Regarding the safety measures, three basic requirements were set out for all the ships covered by the Polar Code (Deggim, 2018). The first requirement is that every ship is subject to certain certification provisions, and the second one is that there are specific minimum requirements about 'performance standards' derived from the standards stipulated in SOLAS (Deggim, 2018). Third, it is mandatory to perform an 'operational assessment' for the ability of a ship to operate in polar waters and the potential risks about the navigation (Deggim, 2018). The Code also involves requirements for polar manual, ship structure, subdivision and stability, fire safety and protection, life-saving appliances and arrangements, navigation safety, voyage planning, etc., (Deggim, 2018). Navigation through the NSR can be affected by not only the international regulations (e.g., Polar Code) but also the domestic ones. Regarding this issue, currently Russia has jurisdiction over most of NSR through its federal law regulations on the NSR and the Rules of Navigation (Solski, 2013; American Bureau of Shipping, 2014). Vessels navigating the NSR need to submit application to the Northern Sea Route Administration (NSRA) of Russia in order to grant permission for the navigation no more than 4 months and no less than 15 days prior to the intended passage through the NSR (American Bureau of Shipping, 2014). Moreover, a vessel's master should notify the NSRA of its estimated arrival time before entry into the NSR area (American Bureau of Shipping, 2014).

2.2.4. Navigation infrastructure

Russian icebreaker fleet has always been a basic necessity to obtaining marine access along the NSR (Moe and Brigham, 2017). The access is achieved by the development of diesel-electric icebreakers and the pioneering use of nuclear-powered icebreakers (Moe and Brigham, 2017). As of 2015, there were 6 diesel-electric icebreakers and 4 nuclear icebreakers (50 years of victory, Yamal, Taymyr, and Vaygach) working in the Russian Arctic (Moe and Brigham, 2017). In practice, Atomflot is the major provider of the icebreaker escort for the long hauls in the Arctic waters (Moe and Brigham, 2017). Compared with the diesel-electric icebreakers, the nuclear icebreakers have the advantages of greater power and ice-breaking ability, and they can maintain for long periods of time without refuelling (Bukharin, 2006). Due to the high costs of maintenance and operation, the fleet of nuclear icebreakers has not yielded profits in recent years (Bukharin, 2006). Russian icebreakers are aging, and many of them will be decommissioned before new ones are operative, which may lead to insufficient icebreaking capacity for the expected growth of Arctic navigation (Moe and Brigham, 2017).

Along the length of NSR, there are several principal Russian ports which include, from west to east, Amderma, Dikson, Dudinka, Igarka, Khatanga, Tiksi, Zeleny Mys, Pevek, and Mys Shmidta (American Bureau of Shipping, 2014; Arctic Council, 2009). Table 3 provides basic information about these ports, which include the depths of anchorage, wharf, and terminal, types of fuel that can be replenished, repair capacity, and availability of rescue station and icebreaker base. For the types of fuel that can be replenished, HFO and MDO indicate 'Heavy Fuel Oil' and 'Marine Diesel Oil' respectively.

Table 3

Basic information about the principle NSR ports

Name of port	Depth at anchorage (m)	Depth at wharf (m)	Depth at terminal (m)	Fuel	Repairs	Rescue station	Icebreaker base
Amderma	11	1.8	-	-	-	-	-
Dikson	7.9	4.9	9.4	HFO,MDO	Limited	Yes	Yes
Dudinka	9.4	6.4	9.4	HFO,MDO	Limited	No	No
Igarka	9.4	11	11	HFO,MDO	Limited	No	No
Khatanga	-	3.4	-	-	Limited	No	No
Tiksi	4.9	4.9	3.4	HFO	Medium	Yes	Yes
Zeleny Mys	1.8	3.4	-	-	Limited	No	No
Pevek	12.5	6.4	6.4	-	Limited	Yes	Yes
Mys	7.9	3.4	-	HFO,MDO	Emergency	No	No

Shmidta

Source: Pastusiak, 2016.

In the NSR ports displayed in Table 3, Igarka, Dudinka, and Khatanga are located at a substantial distance from the NSR (Pastusiak, 2016). There are few reasons that Amderma will become more significant for marine traffic along the NSR (Pastusiak, 2016). Pevek and Dikson can handle vessels with a considerably deep draught at the anchorage, and few ports along the NSR can offer support for vessels which have a draught between 10 m and 20 m (Pastusiak, 2016). The support is especially weak in the eastern section of the NSR which is between Dikson and Pevek (Pastusiak, 2016). Based on Table 3, it can be assumed that there are few opportunities for vessels to receive serious repair in the ports along the NSR, as the nearest Russian ports (e.g., Murmansk and Vladivostok) where repairs can take place are generally outside the NSR (Pastusiak, 2016). Moreover, depths at anchorage and wharf of these ports are often smaller than the drought of vessels for NSR navigation, which makes fuel replenishment in these ports very difficult (Pastusiak, 2016). In light of emergency and rescue services, only 3 out of 9 NSR ports have rescue stations and icebreaker base, and their rescue services are close to the capability limits (Pastusiak, 2016). Based on the above description and analysis, it can be concluded that vessels that navigate through the NSR need to be autonomous during the entire voyage.

The safety of Arctic marine traffic depends heavily on navigation facilities such as fixed and floating, shore-based electronic, and satellite-based navigation aids (Arctic Council, 2009). Vessels navigating the Arctic waters often applies a combination of conventional navigation and satellite positioning techniques (Arctic Council, 2009). A vast network of fixed and floating navigation aids is mainly provided in the Russian ports along the NSR, and the coastal area between the ports has some luminous and nonluminous beacons and daymarks (Arctic Council, 2009). Buoys are put out on the NSR in the ice-free navigation seasons (Pastusiak, 2016). As of 2000, 30 racon type devices and 700 passive radar reflectors were installed in particularly dangerous areas along the NSR, and they were linked with available light and day beacons (Ragner, 2000; Kitagawa, 2001). According to the official nautical publications (National Geospatial-Intelligence Agency, 2010; United Kingdom Hydrographic Office, 2011), vessels should not just depend on radio navigation devices when navigating the entire eastern section of the NSR (Pastusiak, 2016). Satellite positioning systems: GPS and GLONASS could be used by the vessels navigating the NSR in 2000 (Ragner, 2000). However, as positioning systems of vessels based on radio bearings do not function on the NSR, the GPS or GLONASS coordinates of vessels cannot be verified by existing positioning systems (Pastusiak, 2016). In general, the areas of the NSR, especially the eastern section (i.e., Laptev, East Siberian, and Chukchi Seas), face serious underinvestment and investment backlog (Pastusiak, 2016).

As the entire NSR goes along the northern coast of Russia, the paper and electronic charts (ENC) generated by Russia merit special attention (Pastusiak, 2016). As of 1999, there had been already a considerable number of paper and 300 electronic charts provided by Russia, which adequately covers the areas of NSR (Ragner, 2000). Russia is the only provider of ENC for the NSR which cannot be fully covered by the charts of British admiralty, and the scale of the available charts is generally worse than the Russian charts (Pastusiak, 2016). In light of the reliability of the charts, a fact is that the NSR has not been completely studied, which motivates Russia to perform systematic hydrographic surveys of seabed of the NSR (Pastusiak, 2016). However, the reliability of the measurement results are difficult to be validated by international standards (Pastusiak, 2016).

The capacity to acquire the current ice and hydrometeorological information is very important for navigation safety of vessels (Pastusiak, 2016). Such kind of information for vessels navigating the NSR is collected by Russian meteorological service, and it is circulated by means of official weather bulletins for particular forecast regions (SafetyNet) generated by the International Meteorological Organization (Pastusiak, 2016). However, the information presents discrepancies and a high degree of generalization, which suggests limited reliability for the NSR navigation (National Geospatial-Intelligence Agency, 2009; Pastusiak, 2016).

3. The ER Approach

The ER approach is used to aggregate data in this study. It is a generic evidence-based approach for multiple attribute decision analysis (MADA), which is used to address the problems with qualitative and quantitative attributes under uncertainty (Yang and Singh, 1994; Yang and Xu, 2002). In the ER approach, a belief structure is introduced, which is different from traditional MADA methods. Suppose in an MADA problem, a number of alternatives: $D_n\left(n=1,\ldots,N\right)$ need to be assessed based on L attributes or factors, the l^{th} attribute $e_l\left(l=1,\ldots,L\right)$, either quantitative or qualitative, can be assessed among a group of grades $H\ \left(H_1,...,H_K\right)$ that are hypothesized to be collectively exhaustive and mutually exclusive (Kong et al., 2015a). As the attributes $\left(e_1,\ldots,e_L\right)$ may have different relative importance, attribute weight $w_l\ \left(l=1,\ldots,L\right)$ can be used to indicate different degrees of relative importance, which should satisfy the conditions that $w_l \geq 0$ and $\sum_{l=1}^{L} w_l = 1$. The methods for generating attribute weights include subjective (e.g., analytic hierarchical process (AHP), direct rating, SMART, and Delphi), objective (e.g., entropy, principle component analysis (PCA), projection, and standard deviation), and hybrid methods (e.g., integer linear goal-programming, subjective and objective integrated approach, and extension approach of TOPSIS) (Yang et al., 2017). In this study, the AHP method is used to generate attribute weights, which is elaborated in Section 4.3. Let $\beta_{k,l}\left(k=1,\ldots,K;l=1,\ldots,L\right)$ be the degree of belief for the k^{th} assessment grade: H_k in the assessment of e_l. $\beta_{k,l}$ can either be objective if it is a probability generated from data, or subjective if it represents an individual belief (Kong et al., 2015a), and it should meet the condition that $\beta_{k,l} \geq 0$ and $\sum_{k=1}^{K}\beta_{k,l} \leq 1$ (Tang et al., 2012). Table 4 presents the belief decision matrix (Yang and Xu, 2002a) which is used to profile the performance assessment based on the ER approach.

Table 4

The belief decision matrix based on the ER approach

Grades for Attributes Evaluation	Degrees of belief					
	$e_1(w_1)$	$e_2(w_2)$	$\cdots$	$e_l(w_l)$	$\cdots$	$e_L(w_L)$

H_1	$\beta_{1,1}$	$\beta_{1,2}$	$\cdots$	$\beta_{1,l}$	$\cdots$	$\beta_{1,L}$
H_2	$\beta_{2,1}$	$\beta_{2,2}$	$\cdots$	$\beta_{2,l}$	$\cdots$	$\beta_{2,L}$
$\vdots$	$\vdots$	$\vdots$	$\cdots$	$\vdots$	$\cdots$	$\vdots$
H_k	$\beta_{k,1}$	$\beta_{k,2}$	$\cdots$	$\beta_{k,l}$	$\cdots$	$\beta_{k,L}$
$\vdots$	$\vdots$	$\vdots$	$\cdots$	$\vdots$	$\cdots$	$\vdots$
H_K	$\beta_{K,1}$	$\beta_{K,2}$	$\cdots$	$\beta_{K,l}$	$\cdots$	$\beta_{K,L}$

It is clear from Table 4 that we can use a belief distribution: $S(e_l)=\{(H_k,\beta_{k,l}),k=1,\ldots,K;l=1,\ldots,L\}$ to describe an assessment for e_l (Tang et al., 2012). $S(e_l)$ is not complete given that $\sum_{k=1}^{K}\beta_{k,l}<1$ while it is complete given that $\sum_{k=1}^{K}\beta_{k,l}=1$ (Tang et al., 2012). Based upon the belief decision matrix shown in Table 4, we can use the ER algorithm to aggregate the distributed assessments for all the attributes to obtain a combined assessment for an alternative (Kong et al., 2015b). The recursive ER algorithm (Yang and Singh, 1994; Yang and Xu, 2002) for the aggregation is briefly described in the following steps.

Step 1: To transform degrees of belief into basic probability mass.

The degrees of belief $\beta_{k,l}\,(k=1,\ldots,K;l=1,\ldots,L)$ are transformed into basic probability mass by using Eqs. (1) through (4) to merge the related weights and the degrees of belief.

$$m_{k,l}=w_l\beta_{k,l} \tag{1}$$

$$m_{H,l}=1-\sum_{k=1}^{K}m_{k,l}=1-w_l\sum_{k=1}^{K}\beta_{k,l} \tag{2}$$

$$\bar{m}_{H,l}=1-w_l \tag{3}$$

$$\tilde{m}_{H,l}=w_l\left(1-\sum_{k=1}^{K}\beta_{k,l}\right) \tag{4}$$

In Eqs. (1) through (4), $m_{H,l} = \bar{m}_{H,l} + \tilde{m}_{H,l}$ and $\sum_{l=1}^{L} w_l = 1$. $m_{k,l}$ indicates the basic probability mass of e_l which points to the assessment grade H_k. The probability mass assigned to the whole grade set H, is composed of two parts: $\bar{m}_{H,l}$ and $\tilde{m}_{H,l}$, where $\bar{m}_{H,l}$ is elicited by the relative importance of the l^{th} attribute: e_l and $\tilde{m}_{H,l}$ is caused by the incompleteness of assessment on e_l (Wang et al., 2006). $\bar{m}_{H,l}$ is the remaining proportion of beliefs that need to be assigned, depending on how other attributes are evaluated, which indicates to what degree other attributes contribute to evaluating an alternative (Wang et al., 2006). $\bar{m}_{H,l}$ essentially offers a space for resolution of conflict given the existence of conflicting evidence (Wang et al., 2006). $\tilde{m}_{H,l}$ becomes zero given that no ignorance is involved in the assessment (Wang et al., 2006).

Step 2: To combine basic probability mass of e_1 and e_2 into joint probability masses.

Based on Step 1, the basic probability masses for e_1 are generated by Eq. (5).

$$m_{k,1} = w_1 \beta_{k,1},\ \bar{m}_{H,1} = 1 - w_1,\ and\ \tilde{m}_{H,1} = w_1 \left(1 - \sum_{k=1}^{K} \beta_{k,1}\right) \tag{5}$$

It is noted that in Eq. (5), $m_{k,1}$ represents the basic probability mass of e_1 which is assigned to the grade H_k. $\bar{m}_{H,1}$ is generated by the relative importance of e_1, and $\tilde{m}_{H,1}$ is elicited by the incompleteness of e_1. Similarly, we can use Eq. (6) to obtain the basic probability mass for another assessment on e_2.

$$m_{k,2} = w_2 \beta_{k,2},\ \bar{m}_{H,2} = 1 - w_2,\ and\ \tilde{m}_{H,2} = w_2 \left(1 - \sum_{k=1}^{K} \beta_{k,2}\right) \tag{6}$$

The basic probability masses of e_1 and e_2 are combined into the joint probability masses for H_k using Eqs. (7) through (10).

$$\{H_k\}:\ m_{k,e(2)} = J\left(m_{k,1} m_{k,2} + m_{k,1}\left(\tilde{m}_{H,2} + \bar{m}_{H,2}\right) + \left(\tilde{m}_{H,1} + \bar{m}_{H,1}\right) m_{k,2}\right),\ k = 1, \ldots, K$$

(7)

$$\{H\}:\ \tilde{m}_{H,e(2)} = J\left(\tilde{m}_{H,1}\tilde{m}_{H,2} + \tilde{m}_{H,1}\bar{m}_{H,2} + \bar{m}_{H,1}\tilde{m}_{H,2}\right) \tag{8}$$

$$\{H\}:\ \bar{m}_{H,e(2)} = J\left(\bar{m}_{H,1}\bar{m}_{H,2}\right) \quad (9)$$

$$J = \left(1 - \sum_{k=1}^{K}\sum_{t=1,t\neq k}^{K} m_{k,1}m_{t,2}\right)^{-1} \quad (10)$$

Step 3: To combine the assessments recursively.

If there are more than two assessments that are to be combined, we can repeatedly use Eqs. (7) through (10) to combine another assessment with the combined assessment for e_1 and e_2: $m_{k,e(2)}$, $\tilde{m}_{H,e(2)}$, and $\bar{m}_{H,e(2)}$. This process shown in Eqs. (11) through (14) continues until all the assessments are combined recursively. The combined degree of belief assigned to each grade $\left(\beta_{k,e(L)}\right)$ is generated for an alternative using Eqs. (15) and (16) based on the aggregation of the L attributes.

$$\begin{gathered}\{H_k\}:\ m_{k,e(l+1)} = J_{e(l+1)}\left(m_{k,e(l)}m_{k,l+1} + m_{k,e(l)}m_{H,l+1} + m_{H,e(l)}m_{k,l+1}\right),\ l = 1,\ldots,L-1; \\ m_{H,e(l)} = \bar{m}_{H,e(l)} + \tilde{m}_{H,e(l)},\ l = 1,\ldots,L\end{gathered} \quad (11)$$

$$\{H\}:\ \tilde{m}_{H,e(l+1)} = J_{e(l+1)}\left(\tilde{m}_{H,e(l)}\tilde{m}_{H,l+1} + \tilde{m}_{H,e(l)}\bar{m}_{H,l+1} + \bar{m}_{H,e(l)}\tilde{m}_{H,l+1}\right),\ l = 1,\ldots,L-1 \quad (12)$$

$$\{H\}:\ \bar{m}_{H,e(l+1)} = J_{e(l+1)}\left(\bar{m}_{H,e(l)}\bar{m}_{H,l+1}\right),\ l = 1,\ldots,L-1 \quad (13)$$

$$J_{e(l+1)} = \left(1 - \sum_{k=1}^{K}\sum_{t=1,t\neq k}^{K} m_{k,e(l)}m_{t,l+1}\right)^{-1},\ l = 1,\ldots,L-1 \quad (14)$$

$$\{H_k\}:\ \beta_{k,e(L)} = \frac{m_{k,e(L)}}{1-\bar{m}_{H,e(L)}},\ k = 1,\ldots,K \quad (15)$$

$$\{H\}:\ \beta_{H,e(L)} = \frac{\tilde{m}_{H,e(L)}}{1-\bar{m}_{H,e(L)}} \quad (16)$$

In Eqs. (11), $m_{k,e(l)}$ and $m_{H,e(l)}$ indicate the joint probability mass assigned to the grade H_k, and the one not assigned to any grade, respectively, which are generated based on the aggregation of the first l attributes. As $m_{k,e(1)} = m_{k,1}$ and $m_{H,e(1)} = m_{H,1}$, Eqs. (11) through (13) are equivalent to Eqs. (7) through (9), when $l = 1$. In Eq. (16), $\beta_{H,e(L)}$ indicates the remaining degree of belief that is not assigned to any grade H_k (Kong et al., 2015a). It should be mentioned that $\sum_{k=1}^{K} \beta_{k,e(L)} + \beta_{H,e(L)} = 1$, which has been proven by Yang and Xu (2002a). We can use $S(D_n) = \left\{ \left(H_k, \beta_{k,e(L)} \right) \middle| k = 1, \ldots, K \right\}$ to represent the combined assessment for an alternative.

It is clear that the distributed assessments are combined on a one-by-one basis using the recursive ER algorithm, which has the advantage of clarity in its concept (Wang et al., 2006). In situations such as optimization of parameters (e.g., weights of attributes) of models constructed by the ER approach for data classification, we need an analytical ER algorithm shown in Eqs. (17) through (22), which provides an explicit form of ER aggregation function.

$$\{H_k\}: \ m_k = J\left(\prod_{l=1}^{L} \left(m_{k,l} + \bar{m}_{H,l} + \tilde{m}_{H,l} \right) - \prod_{l=1}^{L} \left(\bar{m}_{H,l} + \tilde{m}_{H,l} \right) \right), \ k = 1, \ldots, K \tag{17}$$

$$\{H\}: \ \tilde{m}_H = J\left(\prod_{l=1}^{L} \left(\bar{m}_{H,l} + \tilde{m}_{H,l} \right) - \prod_{l=1}^{L} \bar{m}_{H,l} \right) \tag{18}$$

$$\{H\}: \ \bar{m}_H = J\left(\prod_{l=1}^{L} \bar{m}_{H,l} \right) \tag{19}$$

$$J = \left(\sum_{k=1}^{K} \prod_{l=1}^{L} \left(m_{k,l} + \bar{m}_{H,l} + \tilde{m}_{H,l} \right) - (N-1) \prod_{l=1}^{L} \left(\bar{m}_{H,l} + \tilde{m}_{H,l} \right) \right)^{-1} \tag{20}$$

$$\{H_k\}: \ \beta_k = \frac{m_k}{1 - \bar{m}_H}, \ k = 1, \ldots, K \tag{21}$$

$$\{H\}: \ \beta_H = \frac{\tilde{m}_H}{1 - \bar{m}_H} \tag{22}$$

In Eq. (17), m_k denotes the joint probability mass for the grade H_k. In Eqs. (18) and (19), $\tilde{m}_H$ and $\bar{m}_H$ constitute the joint probability mass that is assigned to the whole grade set H rather than any individual grade. In Eqs. (21) and (22), β_k and β_H are the degree of belief assigned to the grade H_k and the one not assigned to any grade, respectively, in the aggregated result. We can use $S(D_n)=\{(H_k,\beta_k)|k=1,\dots,K\}$ to represent the overall assessment of an alternative D_n, which satisfies the equation that $\sum_{k=1}^{K}\beta_k+\beta_H=1$ (Tang et al., 2012).

The recursive and analytical ER algorithms are equivalent (Wang et al., 2006). The analytical ER algorithm provides the ER approach with more flexibility to aggregate a large number of attributes (or environmental factors) (Wang et al., 2006), which features nonlinearity (Yang and Xu, 2002b) and makes it easy to estimate and optimize the parameters such as weights of attributes (Wang et al., 2006). It also offers a direct way to perform sensitivity analysis for the ER approach parameters, e.g., degree of belief and weight (Wang et al., 2006). Of note is that the recursive and analytical ER algorithms do not have issues of convergence, as only a finite number of attributes are taken into consideration in an MADA problem (Wang et al., 2006). In this study, the analytical ER algorithm is applied to the aggregation of the distributed assessments which is implemented using a decision support software 'Intelligent Decision System (IDS)' (Xu and Yang, 2005).

The distributed assessment for each attribute can be used to identify the strengths and weaknesses of each alternative (Kong et al., 2015b). However, the results of distributed assessment may not be directly used to rank alternatives (Kong et al., 2015b). To facilitate the ranking on one or all attributes, a single score is needed to denote the performance for each alternative (Kong et al., 2015b). The expected utility is used by Yang and Xu (2002a) to produce a single numerical value based on each distributed assessment to rank alternatives. It is generated by $\mu(E)=\sum_{k=1}^{K}\beta_k\mu(H_k)$ where $\mu(E)$, β_k, and H_k represent the expected utility, the degree of belief assigned to the grade H_k in the aggregated result, and the k^{th} assessment grade, respectively. It will be demonstrated in Section 4 of this paper.

Overall, there are several advantages for using the ER approach to assess the safety risk for the marine traffic in the Arctic waters. First of all, a new framework of belief is provided to establish models and synthesize subjective and objective environmental factors for safety of Arctic marine traffic under high uncertainty. In the second place, we can use the ER approach to generate distributed assessments and the contributing factors for safety environments of the marine traffic in different Arctic waters. Thus, we can compare the strengths and weaknesses of different safety environments for Arctic marine traffic. Additionally, the distributed assessments can be used to generate the numerical safety scores by the ER approach to help us decide which Arctic water area is more navigable. Furthermore, only judgement independence among contributing factors of safety is required in the ER approach, which is comparatively easy to check (Xu et al., 2006). Despite these advantages, the ER approach has some limitations. Compared with other information aggregation methods, the ER approach represents both qualitative information and quantitative data in belief distributions, which essentially requires more granular information and data and also increases computational complexity. In addition, if there is no local and global ignorance in the problems, the ER approach is reduced to Bayesian inference, which has a wider range of software tools for implementation.

4. Application of the ER approach to the Arctic waters

According to the domain knowledge, expert discussions, and literature analysis for the relevant studies, a set of environmental factors of safety are selected from 4 aspects introduced and justified in Section 2.2 to reflect the characteristics of the Arctic marine traffic environment. Using these factors, a hierarchical model is established for the safety evaluation of Arctic marine traffic, which is displayed in Fig. 1. There are three levels in the model. The top level, ‘General criterion level’, indicates the safety of the Arctic marine traffic environment, which is the output of the evaluation. The second level, the criteria level, indicates 4 environmental criteria (aspects of environmental factors) of safety, namely, hydrometeorology, channel, traffic regulation, and navigation infrastructure. The third level, i.e., the sub-criteria level, which is based on the second level, includes the environmental sub-criteria (environmental factors) of safety used as the input for the evaluation. All of these sub-criteria can be evaluated directly through quantitative data or qualitative judgements. Based on the hierarchical model, the ER approach is used to evaluate the safety of Arctic marine traffic environment following the research steps explained below.

4.1. Step 1: Definition of evaluation grades of safety

Evaluation grades of safety are the unified benchmark for quantitative data collected from the vessel ‘Tian You’ and qualitative judgements from domain experts for the environmental sub-criteria. A set of five-degree evaluation grades of safety is used in this study, which includes ‘Best’, ‘Good’, ‘Fair’, ‘Poor’, and ‘Worst’. The five-degree grades are applied to each level of the hierarchical model. They are established based on the relevant studies (e.g., Khan et al., 2014; Kum and Sahin, 2015; Fu et al., 2016), reports (e.g., Arctic Council, 2009; American Bureau of Shipping, 2014), international codes (Deggim, 2018), and intensive discussions with domain experts. In light of the mapping relationship of evaluation results between adjacent levels, it is assumed in this study that the evaluation result of each grade in the lower level are completely transformed to the same relevant grade in the upper level. An example is that the ‘fair’ in the lower level can be transformed to its counterpart in the upper level with a belief degree of 100%.

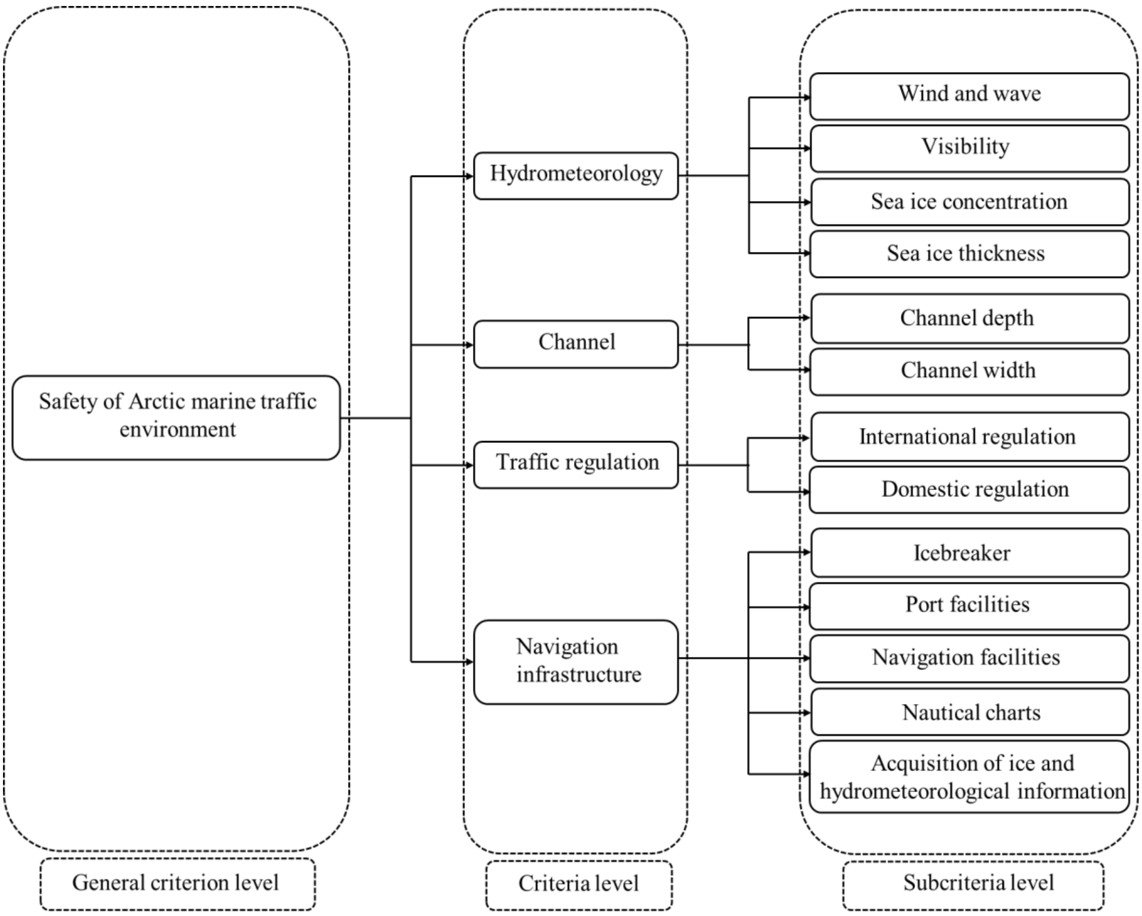


Fig. 1. The hierarchical model for environmental evaluation of Arctic marine traffic

4.2. Step 2: Data input

The five-degree evaluation grades of safety are well defined for different environmental sub-criteria. Here, ‘International regulation’ is taken as an example to interpret the five-degree grades. ‘Best’ indicates a comprehensive and excellent regulation system with a very strict implementation; ‘Good’ denotes a satisfactory one with a strict implementation; ‘Fair’ represents an acceptable one with a normal implementation; ‘Poor’ means a barely acceptable one with a weak implementation; ‘Worst’ signifies that there is currently no appropriate regulation system. Another example is ‘Sea ice concentration’. In this environmental factor, ‘Best’, ‘Good’, ‘Fair’, ‘Poor’, and ‘Worst’ indicate that the sea ice concentration is perfectly suitable, suitable, acceptable, barely acceptable, and unacceptable, respectively, for navigation.

Based on the set of five-degree grades, quantitative data are transformed to distributed assessments based on a belief structure. To perform such a transformation, it is fundamental to decide the rules about linking a specific numerical value to each evaluation grade (Yang, 2001a). Suppose that a referential value $A_{k,l}\left(k=1,\ldots,K;l=1,\ldots,L\right)$ for the l^{th} environmental sub-criterion is equivalent to an evaluation grade H_k . $A_{1,l}$ and $A_{K,l}$ are the smallest and largest feasible value respectively, and a referential value $A_{k+1,l}$ is preferred to a smaller one $A_{k,l}$. Given that $x_{i,l}$ is the i^{th} numerical value of the l^{th} environmental sub-criterion, $x_{i,l}$ can be transformed into a belief distribution of evaluation grades using Eqs. (23) and (24) (Yang, 2001b).

$$S_i\left(x_{i,l}\right)=\left\{\left(A_{k,l},\alpha_{k,i}\right)\middle|k=1,\ldots,K;l=1,\ldots,L;i=1,\ldots,T\right\} \tag{23}$$

where

$$\alpha_{k,i}=\frac{A_{k+1,l}-x_{i,l}}{A_{k+1,l}-A_{k,l}},\ \alpha_{k+1,i}=1-\alpha_{k,i},\ \text{if } A_{k,l}\le x_{i,l}\le A_{k+1,l} \tag{24}$$

In Eqs. (23) and (24), $S_i\left(x_{i,l}\right)$ represents the belief distribution of evaluation grades for $x_{i,l}$, and $\alpha_{k,i}$ indicates the similarity degree to which $x_{i,l}$ matches the referential value $A_{k,l}$. To illustrate how to transform continuous numerical values into distributed assessments, ‘Sea ice concentration’ is taken as an example. According to Pastusiak (2016), if the sea ice concentration ranges between 0% and 10%, a vessel can navigate at full operating speed over a long period of time, and it can be kept away from any ice floes on the sea route without a significant speed reduction. When the sea ice concentration is greater than 10% but less than 15%, a vessel can navigate without obstruction (Pastusiak, 2016). If the ice concentration is between 15% and 40%, a vessel can maintain operating speed for about 3/4 of the sea route, and needs to reduce speed for approximately 1/4 of the route (Pastusiak, 2016). Sea ice concentration worsens when it is between 40% and 70%. It becomes impossible for independent navigation of vessels, if the sea ice concentration exceeds 70% (Pastusiak, 2016). Let 0%, 15%, 40%, 70%, and 100% be the referential values for ‘Best’, ‘Good’, ‘Fair’, ‘Poor’, and ‘Worst’, respectively. Given that the sea ice concentration is 30%, we can obtain the associated belief degrees: 40% $\left(\frac{40\%-30\%}{40\%-15\%}=40\%\right)$ and 60% $\left(1-\frac{40\%-30\%}{40\%-15\%}=60\%\right)$ for the evaluation grades: ‘Good’ and ‘Fair’, respectively. Table 5 provides the sets of referential values for sub-criteria in ‘Hydrometeorology’ (except the sub-criteria of ‘Wind and wave’ and ‘Visibility’) and ‘Channel’. In terms of ‘Wind and wave’, the transformation rule between Beaufort levels and the evaluation grades is that Beaufort level 0-2, 3-5, 6-7, 8-9, and 10-12 respectively indicate ‘Best’, ‘Good’, ‘Fair’, ‘Poor’, and ‘Worst’. For ‘Visibility’, the transformation rule from visibility level to the evaluation grades is that level 1-2, 3-4, 5-6, 7-8, and 9-10 are linked to ‘Worst’, ‘Poor’, ‘Fair’, ‘Good’, and ‘Best’, respectively.

In this study, we sampled hydrometeorological data (average values) at specific dates of three locations in East Siberian, Laptev, and Kara Sea for the environmental evaluation, which are displayed in Table 6. Regarding the tempo-spatial resolution of the data, as mentioned, all the quantitative data (including sea ice concentration and thickness, and channel depth and width) were collected in the period between the 26th August and the 20th September in 2019 which is within the window period for the navigation in the Russian Arctic waters. Thus, the collected quantitative data can be considered consistent in the temporal dimension. According to the captain of ‘Tian You’, the speed of ‘Tian You’ is 12 knots at most time of the Arctic voyage. In two days, ‘Tian You’ can sail about $12 \times 24 \times 2 = 576$ nautical miles (nmi) ≈ 1066.752 km. Since the distance between any two of the three vessel locations (sampled respectively on September 8th, 10th, and 12th in 2019) is larger than 1,000 km, the hydrometeorological data including the ice data of any two locations can be generally considered independent from each other.

Table 5

Referential values for hydrometeorological and channel data

Evaluation grades	Sea ice concentration (%)	Sea ice thickness (cm)	Channel depth (m)	Channel width (nmi)
Best	0	0	1000	1000
Good	15	30	100	100
Fair	40	100	50	30
Poor	70	200	20	6
Worst	100	500	4	1

Source: Arctic Council, 2009; Pastusiak, 2016.

Table 6

Hydrometeorological and channel data for three locations of ‘Tian You’ in the Arctic waters

Name of sea that the location belongs to	Date	Latitudes and longitudes of Vessels locations at 12:00 pm of the date	Wind and wave (Beau-fort level)	Visibility (level)	Sea ice concent-ration (%)	Sea ice thick-ness (cm)	Chan-nel depth (m)	Chan-nel width (nmi)
East Siberian Sea	Sept. 8th, 2019	$71^{\circ}5.5N$, $163^{\circ}27.3E$	3	7	0	0	22.95	620

Laptev Sea	Sept. 10th, 2019	$74^{\circ}50.4N$, $135^{\circ}15.2E$	7	6	0	0	36.1	67.8
Kara Sea	Sept. 12th, 2019	$77^{\circ}50.8$, $96^{\circ}44.0$	3	7	16	210	139.5	104

For the qualitative environmental sub-criteria (e.g., 'Port facilities' and 'Nautical charts'), expert judgements based on the knowledge provided in Section 2.2 were collected from 8 domain experts in the relevant fields as mentioned in Section 2.1, and they are merged with the same weights due to the experts' similar backgrounds. The combined expert judgements are in the form of belief degree distribution, i.e., $\{\beta_B, \beta_G, \beta_F, \beta_P, \beta_W\}$ in which $\beta_B, \beta_G, \beta_F, \beta_P$, and $\beta_W \subseteq [0,1]$, and $\beta_B + \beta_G + \beta_F + \beta_P + \beta_W \leq 1$. $\beta_B, \beta_G, \beta_F, \beta_P$, and β_W indicate the belief degrees distributed to the evaluation grades: 'Best', 'Good', 'Fair', 'Poor', and 'Worst', respectively. If the sum of the belief degrees is less than 1, the judgement is considered to be incomplete, and there is uncertainty in input data. For instance, a combined result of expert judgements $\{0.5, 0.3, 0.1, 0, 0\}$ indicates that based on the judgements, we should have a credence of 50%, 30%, 10% in the truth of 'Best', 'Good', and 'Fair', respectively, and we have complete confidence that 'Poor' and 'Worst' are not true. The remaining 10% in the result is for uncertainty caused by ignorance or lack of knowledge. Using the data and judgement transformation techniques illustrated in this section, we can obtain the evaluation results of all the environmental sub-criteria of safety for the location in East Siberian Sea, which are displayed in Table 7. The results for other locations in Laptev Sea and Kara Sea are displayed in Appendix. A.

Table 7

Evaluation results of all the environmental sub-criteria for the location of 'Tian You' in East Siberian Sea

Criteria	Sub-criteria	Belief degrees for evaluation grades				
		Best	Good	Fair	Poor	Worst
Hydrometeorology	Wind and wave	0	1	0	0	0

	Visibility	0	1	0	0	0
	Sea ice concentration	1	0	0	0	0
	Sea ice thickness	1	0	0	0	0
Channel	Channel depth	0	0	0.10	0.90	0
	Channel width	0.58	0.42	0	0	0
Traffic regulation	International regulation	0.07	0.71	0.12	0	0
	Domestic regulation	0	0.34	0.57	0	0
Navigation infrastructure	Icebreaker	0	0	0.16	0.54	0.22
	Port facilities	0	0	0.03	0.20	0.68
	Navigation facilities	0	0	0.27	0.30	0.36
	Nautical charts	0	0.22	0.63	0.05	0
	Acquisition of ice and hydrometeorological information	0	0.18	0.53	0.21	0

4.3. Step 3: Calculation of weights

In this study, the AHP method (Ahn, 2017; Forman and Gass, 2001; Saaty, 1986, 1980) was used to determine the weights for criteria and sub-criteria used in assessments aggregation. First of all, pairwise comparison based on a relative importance scale (shown in Table 8) was conducted for criteria and sub-criteria among 8 experts from the domains mentioned in Section 2.1. These experts are from maritime shipping companies, maritime universities, maritime authorities, and classification societies. Their backgrounds including qualifications and working experience are similar. The sources from which they obtain information about the safety environment of Arctic marine traffic are basically the same, which include Russian maritime authorities, websites about related information, and shipping companies such as COSCO Shipping. Their knowledge about the safety environment of Arctic marine traffic is similar. Considering all the above facts, each expert's judgement for pairwise comparison is assigned the same weight. Using these weights, the expert judgements are merged to generate 5 pairwise comparison matrices in terms of the levels of criteria and sub-criteria. Given the criteria or sub-criteria: $A_1,...,A_n$, these pairwise comparison matrices are in the form of matrix A shown in Eq. (25).

$$A=\left(a_{ij}\right)_{n\times n}=\begin{bmatrix} 1 & a_{12} & \cdots & a_{1n} \\ \frac{1}{a_{12}} & 1 & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{1}{a_{1n}} & \frac{1}{a_{2n}} & \cdots & 1 \end{bmatrix} \tag{25}$$

In matrix A, a_{ij} indicates the ratio of relative importance between A_i and A_j. Furthermore, we can calculate the weighting vector of index k using Eq. (26).

$$w_k=\frac{1}{n}\sum_{j=1}^{n}\left(\frac{a_{kj}}{\sum_{i=1}^{n}a_{ij}}\right)\quad\left(k=1,...,n\right) \tag{26}$$

As shown in Eq. (26), w_k, the weight for A_k, is the arithmetic average of entries of the matrix which is composed of normalized column vectors of matrix A.

Table 8

Importance scale of pairwise comparison

Importance scale	Definition
1	Equal importance
3	Weak importance of one over another
5	Strong importance
7	Very strong importance
9	Extreme importance
2, 4, 6, 8	Intermediate values between two adjacent judgements
Reciprocals	If one of the above number is assigned to criterion i which is in comparison with criterion j, j is assigned reciprocal value when compared with i.

Data source: Saaty, 1990.

To check whether the comparison judgement is reasonable, the consistency ratio is used. The judgement is considered to be reasonable, if the consistency ratio (CR) is not greater than 0.10 (Anderson et al., 2003). The ratio can be approximated by the Eq. (27).

$$CR = \frac{CI}{RI} \tag{27}$$

In Eq. (27), CR is abbreviated for consistency ratio. CI represents consistency index which can be generated using Eq. (28). RI is short for random index based on the size of matrix which is shown in Table 9.

$$CI = \frac{\lambda_{\max} - n}{n-1} \tag{28}$$

In Eq. (28), $\lambda_{\max}$ is the largest eigenvalue of matrix A.

Table 9

Average values of random index

Size of matrix	2	3	4	5	6	7	8	9	10
RI	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

Data source: Anderson et al., 2003.

By using the method described above, the weights for criteria and sub-criteria are displayed in Table 10. All of the consistency ratios for the pairwise comparisons are less than 0.1, hence the inconsistency of the comparison judgements is acceptable.

Table 10

Weights for criteria and sub-criteria in the hierarchical model

Criteria	Weights	Sub-criteria	Weights
Hydrometeorology	0.4778	Wind and wave	0.1570
		Visibility	0.0882
		Sea ice concentration	0.4829

		Sea ice thickness	0.2720
Channel	0.2561	Channel depth	0.6667
		Channel width	0.3333
Traffic regulation	0.1281	International regulation	0.3333
		Domestic regulation	0.6667
Navigation infrastructure	0.1380	Icebreaker	0.1345
		Port facilities	0.0850
		Navigation facilities	0.1105
		Nautical charts	0.2379
		Acquisition of ice and hydrometeorological information	0.4322

It is noted that both ER and AHP can be used based on the structure of Fig. 1 to generate assessments of alternatives. With ER, the degree of belief is generated for each sub-criterion of model independently, while the logic of AHP model works at the highest level (e.g., the criteria level), and uses pair-wise comparison to assess the alternatives against each other (Dehe and Bamford, 2015). It is not practical to facilitate the pairwise comparison process to identify the weights and assessments for a large number of sub-criteria. The weighting and assessment process of ER can generate good consistency while the pairwise comparison process of AHP is less consistent (Dehe and Bamford, 2015). ER is a more transparent process than the pairwise comparison on which AHP is based (Dehe and Bamford, 2015). ER is easy to track, while AHP does not keep track of what happen during the process of pairwise comparison for weights and assessments. A reliable and appropriate modeling technique to use in the context of safety assessment is a hybrid method of ER and AHP that is the use of ER to aggregate assessments based on degrees of belief for sub-criteria and criteria, merged with the AHP method based on pairwise comparison to generate weights of criteria and sub-criteria .

4.4. Step 4: Aggregation of distributed assessments and calculation of utilities

Based on the weights of criteria and sub-criteria, the belief degrees of evaluation grades are aggregated level by level through the analytical ER algorithm introduced in Eqs. (17) through (22) of Section 3 to achieve the distributed assessments of the 'General criterion level' for different locations in the Arctic waters. The calculation of the aggregation is performed using a decision support software 'Intelligent Decision System (IDS)' (Xu and Yang, 2005). With the distributed assessments, we can compare how safe vessels are in different locations of the Arctic waters. To make a more intuitive comparison among the safety of different locations, we need to rank these locations using the expected utilities that are equivalent to distributed assessments. To achieve the ranking, first of all, we need to assign utility value to each evaluation grade (Yang and Xu, 2002c). In this study, a set of utility values: 0, 0.25, 0.5, 0.75, and 1 are assigned to the evaluation grades: 'Worst', 'Poor', 'Fair', 'Good', and 'Best', respectively. Here, we use H_k to indicate an evaluation grade, and $\mu\left(H_k\right)$ to denote its utility. If H_{k+1} is preferable to H_k, $\mu\left(H_{k+1}\right) > \mu\left(H_k\right)$ (Yang and Xu, 2013). The utility of the general criterion can be generated using Eq. (29).

$$\mu\left(E\right) = \sum_{k=1}^{K} \beta_k \mu\left(H_k\right) \tag{29}$$

Thus, based on Eq. (29), the distributed assessments can be transformed into a utility value for each location, and we can rank these locations in terms of their utilities of safety.

4.5. Step 5. Sensitivity analysis

The sensitivity analysis is performed to validate the soundness of the proposed hierarchical model, which is very important when subjective judgements are involved in the model. In this study, the sensitivity analysis was conducted to observe how sensitive the output of an evaluation model is to the slight changes in the weights of criteria of the proposed model.

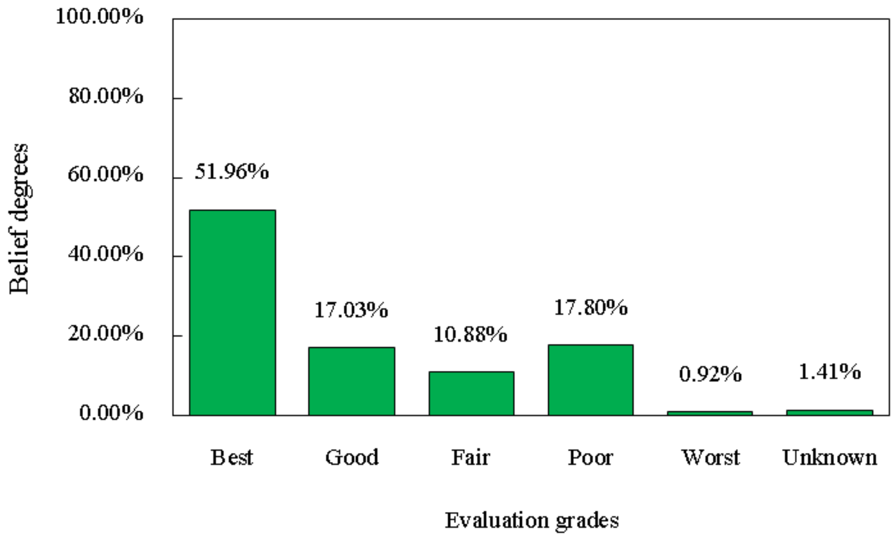
5. Results and discussion

Using the data inputs and methods illustrated in Sections 2, 3, and 4, we can achieve the distributions of belief degrees of evaluation grades in the 'Criteria level' and 'General criterion level' of the model, which are shown in Table 11 and Fig. 2, respectively.

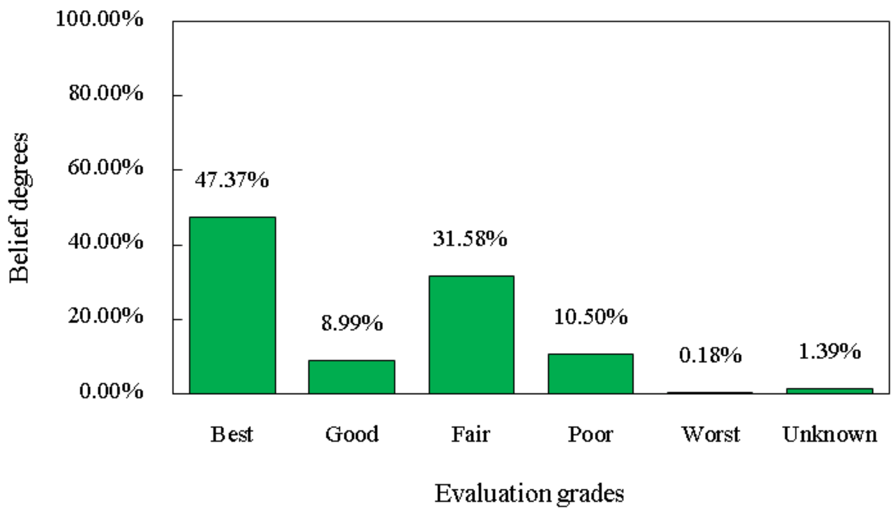
Table 11

The distribution of belief degrees of evaluation grades in 'Criteria level' for 3 locations in East Siberian, Laptev, and Kara Sea

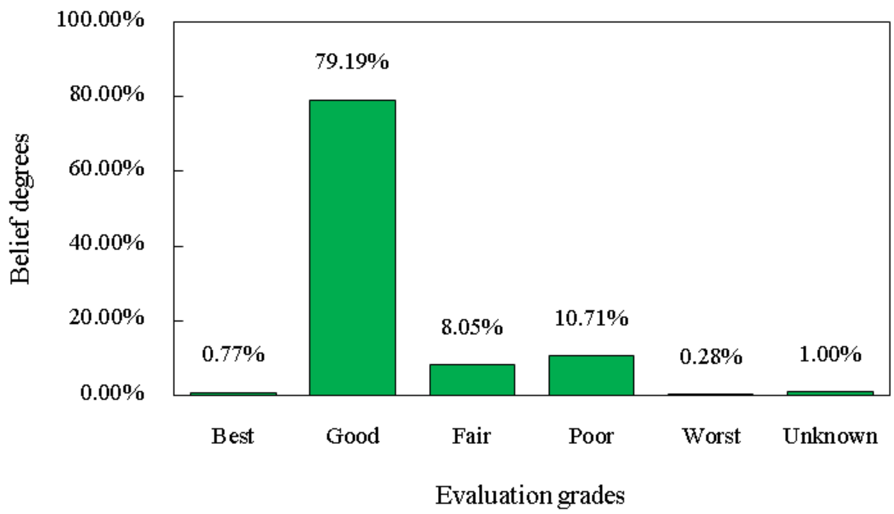
Criteria	Sea of locations	Best	Good	Fair	Poor	Worst	Unknown
Hydrometeorology	East Siberian	0.846	0.154	0	0	0	0
	Laptev	0.846	0	0.154	0	0	0
	Kara	0	0.781	0.020	0.193	0.006	0
Channel	East Siberian	0.116	0.084	0.080	0.720	0	0
	Laptev	0	0.098	0.567	0.335	0	0
	Kara	0.023	0.977	0	0	0	0
Traffic regulation	East Siberian	0.014	0.460	0.447	0	0	0.080
	Laptev	0.027	0.615	0.281	0	0	0.077
	Kara	0.049	0.558	0.329	0	0	0.065
Navigation infrastructure	East Siberian	0	0.132	0.482	0.217	0.095	0.073
	Laptev	0	0.124	0.455	0.328	0.019	0.075
	Kara	0	0.208	0.542	0.185	0	0.066



(a) East Siberian Sea



(b) Laptev Sea



(c) Kara Sea

Fig. 2. The distribution of belief degrees of evaluation grades in 'General criterion level' for 3 locations in East Siberian, Laptev, and Kara Sea

From Table 11, it can be found that the 3 locations in East Siberian, Laptev, and Kara Sea generally have similar distributions of belief degrees in terms of 'Traffic regulation' and 'Navigation infrastructure'. In light of 'Hydrometeorology', both East Siberian and Laptev Sea have a large belief degree in the grade 'Best', while a small one distributed in 'Good' and 'Fair'. For the 'Channel', East Siberian, Laptev, and Kara Sea have a prevailing high belief degree in 'Poor', 'Fair', and 'Good', respectively, and small belief degrees in other grades. In Fig. 2, it is clear that the belief degree distribution of Kara Sea is significantly different from the distributions of East Siberian and Laptev Sea which are similar. It should be noted that the part of 'Unknown' present in the evaluation indicates the experts' epistemic uncertainties which may come from knowledge and information deficit, partial understanding, underconfidence in judgements, etc.

To compare the safety level of the locations more intuitively, the utilities of the general criterion for the locations in the three seas were generated using Eq. (23), which transforms distributed assessments to numerical values to facilitate ranking. In this study, the larger the utility is, the more safely a vessel can navigate in the Arctic waters. As the 'Unknown' part of the evaluation results can be assigned to the grades of 'Best' and 'Worst' to respectively generate the expected maximum and minimum utilities, we can use the average value of the minimum and maximum utilities to rank the safety level of these locations. Table 12 displays the minimum, maximum, and average utilities of the locations in terms of criteria, and Fig. 3 presents the overall minimum, maximum, and average utilities of the locations.

Table 12

The minimum, maximum, and average utilities of 3 locations of Arctic waters in the 'Criteria' level

Criteria	Location	Minimum utility	Maximum utility	Average utility
Hydrometeorology	East Siberian	0.9616	0.9616	0.9616
	Laptev	0.9231	0.9231	0.9231
	Kara	0.6441	0.6441	0.6441
Channel	East Siberian	0.3990	0.3990	0.3990
	Laptev	0.4409	0.4409	0.4409
	Kara	0.7558	0.7558	0.7558
Traffic regulation	East Siberian	0.5818	0.6618	0.6218
	Laptev	0.6289	0.7059	0.6674
	Kara	0.6314	0.6962	0.6638
Navigation infrastructure	East Siberian	0.3947	0.4675	0.4311
	Laptev	0.4020	0.4772	0.4396
	Kara	0.4730	0.5388	0.5059

Of note is that the minimum, maximum, and average utilities of each location in the criteria of 'Hydrometeorology' and 'Channel' are equal, while those in 'Traffic regulation' and 'Navigation infrastructure' are different, as the former ones were calculated based on quantitative data collected from voyage of 'Tian You' and the latter ones were generated based on the expert judgements. From Table 12, it is clear that the average utilities of the locations in the criteria of ‘Traffic regulation’ and ‘Navigation infrastructure’ are distributed in the narrow ranges of 0.62-0.67 and 0.43-0.51. This suggests that the traffic regulation systems for the three locations are generally satisfactory while the navigation infrastructure of the locations is in an average condition which may need improvement. In light of ‘Hydrometeorology’, East Siberian and Laptev Sea achieve high average utilities approaching 1, which are far better than the counterpart of Kara Sea. This indicates that the hydrometeorological environment of East Siberian and Laptev Sea in the first half of September is very suitable for the vessels navigation. On the contrary, in the criterion of ‘Channel’, Kara Sea has a utility value of 0.7558 while the utilities of the other two seas are in a range of 0.39-0.45. This tells us that the geographical condition of Kara Sea is satisfactory while the geographical conditions of East Siberian and Laptev Sea are barely acceptable.

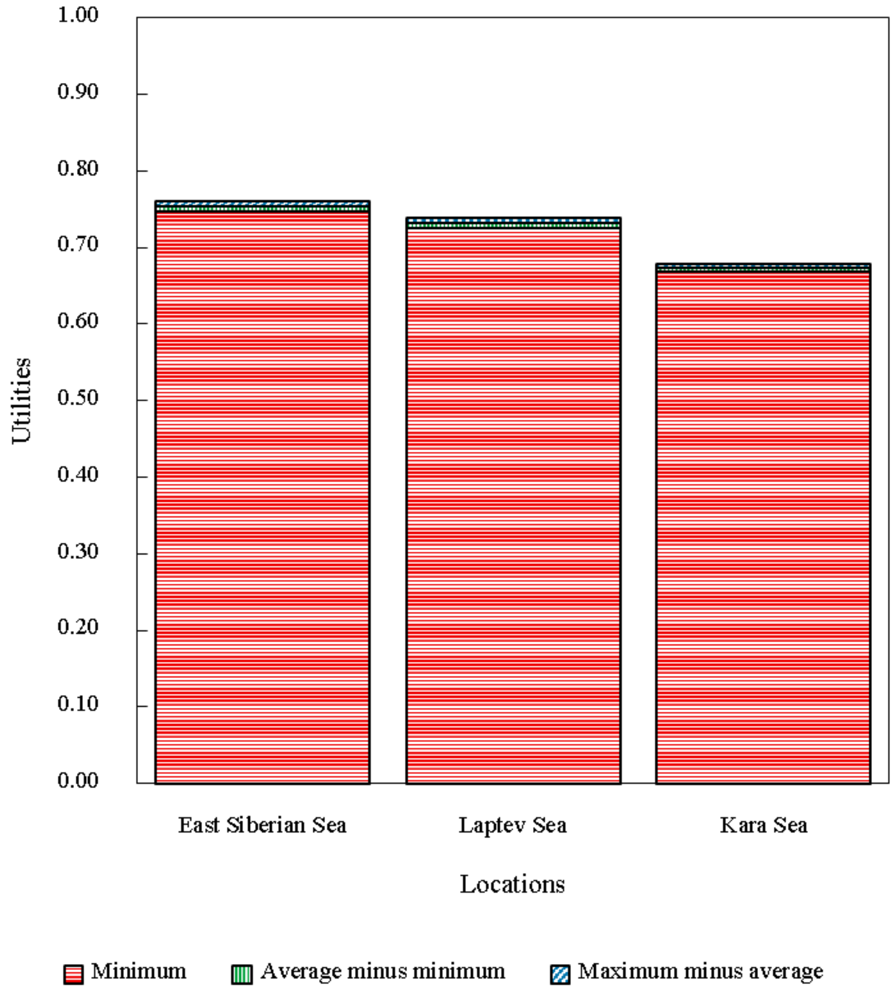


Fig. 3. The overall minimum, average, maximum utilities of 3 locations of Arctic waters

In terms of the overall utilities of the locations, East Siberian Sea ranks the first, which has an average utility of 0.7532, followed by Laptev and Kara Sea with respective utilities of 0.7322 and 0.6736. It is of note that the uncertainties (green and blue parts of Fig. 3) present in the overall utilities do not affect the final ranking of the locations as they are all less than 0.008. The overall utilities of these locations imply that the environment of the locations in East Siberian and Laptev Sea is generally suitable for vessels navigation in the first half of September, which is significantly better than that of Kara Sea.

To test the soundness of the model, we conducted the sensitivity analysis which focuses on how the variations of weights affect the overall utilities of the vessel locations. The weights play an important role in the variation of utilities. The increase or decrease of weight of a given criterion can lead to associated increase or decrease of average utility of a vessel location which has a good performance in the given criterion. Based on the fact, two hypotheses have been proposed to validate the soundness of the model.

Hypothesis 1: The increase of the weight of the criterion ‘Hydrometeorology’ will lead to the increase of the average utility of ‘East Siberian Sea’.

Hypothesis 2: The increase of the weight of the criterion ‘Channel’ will lead to the increase of the average utility of ‘Kara Sea’.

The weights of ‘Hydrometeorology’, ‘Channel’, ‘Traffic regulation’, and ‘Navigation infrastructure’ in the criteria level are approximately 0.48, 0.26, 0.13, and 0.14 respectively. To study how the increase of the weight of ‘Hydrometeorology’ affects the average utility of ‘East Siberian Sea’ (Hypothesis 1), the weight of ‘Hydrometeorology’ is increased from about 0.48 to about 1 with a step of 0.03, while the weights of other criteria are decreased simultaneously and they share the same ratio. The change of weights and the associated change of utilities are shown in Fig. 4, and Table A-III of Appendix. A displays all the relevant weights and utilities for the data points of Fig. 4. For Hypothesis 2, we focus on the variation of the average utilities of ‘Kara Sea’ with the change of weight of ‘Traffic regulation’. Fig. 5 presents the variation of weights and the associated variation of utilities, and all the relevant weights and utilities for the sensitivity analysis of weight of ‘Channel’ (Fig. 5) are shown in Table A-IV of Appendix. A.

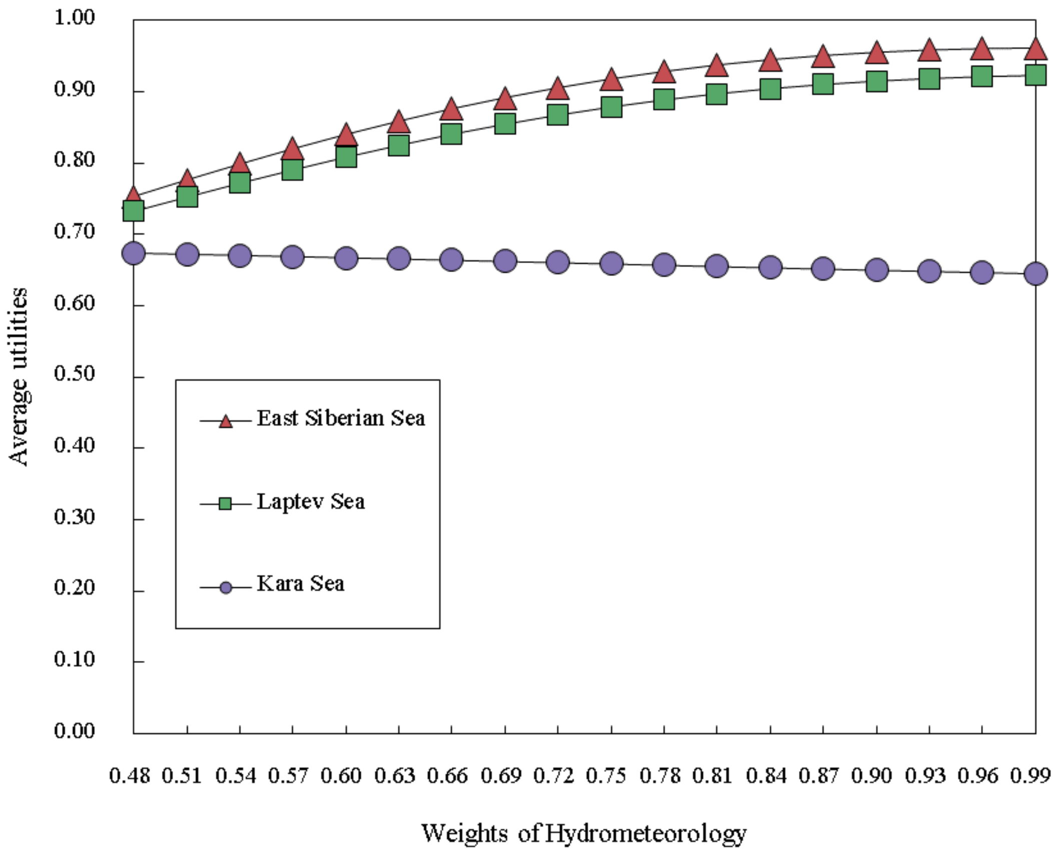


Fig. 4. Variation tendency of utilities with change of weights of Hydrometeorology

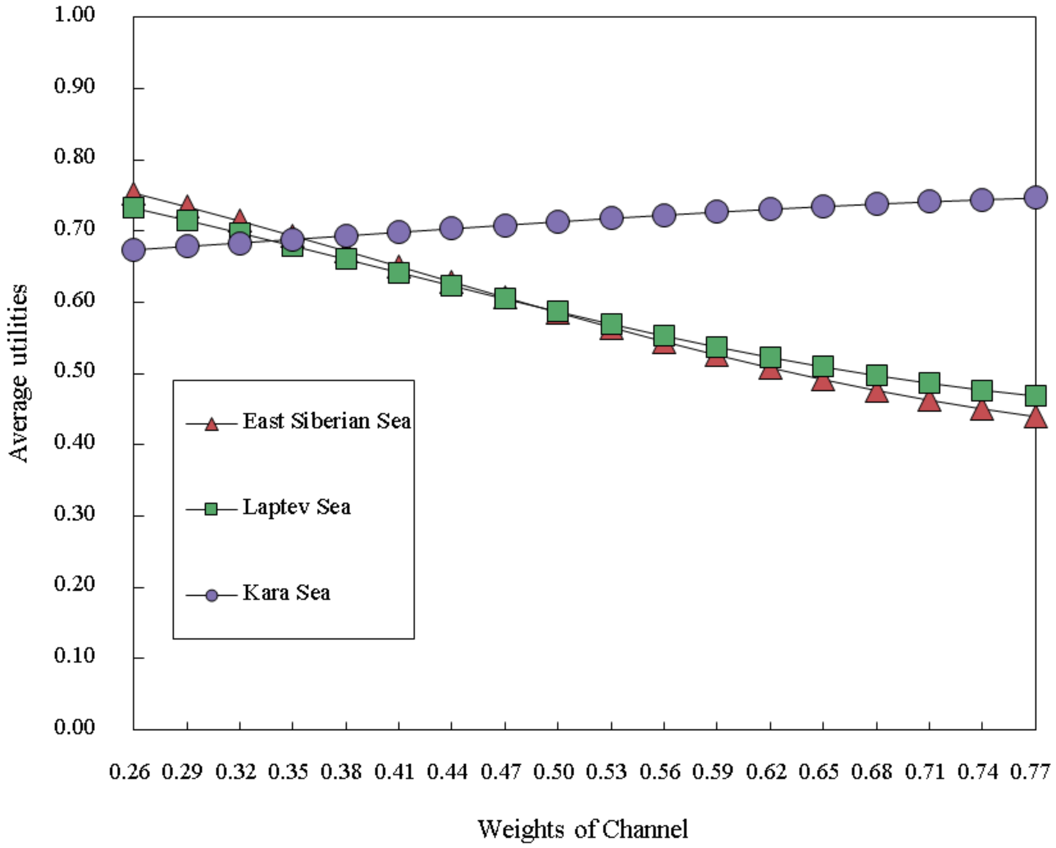


Fig. 5. Variation tendency of utilities with change of weights of Channel

As shown in Fig. 4, there is a significant growing tendency for the utilities of East Siberian Sea when the weight of 'Hydrometeorology' is increased. The increasing tendency for the utilities of 'Kara Sea' is also observed in Fig. 5 where the weight of 'Channel' is increased from about 0.26 to about 0.77. These findings verify that the Hypotheses 1 and 2 that we propose in this section are tenable, which indicates that the proposed model in this study is rational and feasible.

6. Conclusions

In this paper, a new model based on the ER approach is proposed for the safety evaluation of Arctic marine traffic environment. 13 sub-criteria from perspectives of 'Hydrometeorology', 'Channel', 'Traffic regulation', and 'Navigation infrastructure' are considered in the model. A case study based on the NEP voyage of the general cargo vessel 'Tian You' is conducted to illustrate how to use the ER approach to establish the model and conduct a sensitivity analysis to validate the model. The evaluation results show that the locations in East Siberian and Laptev Sea generally have a better navigation environment than the one in Kara Sea, but the navigation infrastructure in East Siberian and Laptev Sea needs to be improved. The results of sensitivity analysis validate the rationality and feasibility of the model.

Despite the disadvantages of the ER approach, the major advantage of the use of ER approach in this paper is that it can synthesize the objective data and subjective judgements in the new model to generate the distributed assessments for the safety level of navigation environment and its contributing criteria and sub-criteria, while it considers the uncertainties existing in the evaluation due to knowledge deficit, inexperience, underconfidence, etc. The distributed assessments and utility values are used to prioritize the safety levels of vessel locations. In addition, the quantitative environmental data were collected from the Arctic navigation records of the general cargo vessel "Tian You". The qualitative expert judgements were acquired from questionnaires distributed to domain experts. All of this first-hand material reflects the real safety environment of Arctic navigation. Besides, the environmental factors including hydrometeorology, channel, traffic regulation, and navigation infrastructure are systematically reviewed in this paper, which provides a panorama of the Arctic navigation environment. While the new model of this study is specifically for safety evaluation of the Arctic marine traffic, the principle and the process for developing this model is applicable to environmental evaluation of safety for similar marine traffic such as Antarctic marine traffic.

This study inevitably has limitations. In the first place, only a limited number of environmental sub-criteria of safety are involved in the model, which may not comprehensively profile the Arctic navigation environment. Further investigation based on domain knowledge will be carried out to include more associated environmental sub-criteria of safety in the model. Another issue is about the reliability of expert judgement. The questions in the questionnaire may not be explicit enough, which may lead to bias and misunderstanding. A higher level of questionnaire hence needs to be designed to further improve the evaluation results.

Appendix. A. The evaluation results of all the environmental sub-criteria for the locations of 'Tian You' in Laptev and Kara Sea, and the relevant weights and utilities for the sensitivity analysis

Table A-I

Evaluation results of all the environmental sub-criteria for the location of 'Tian You' in Laptev Sea

Criteria	Sub-criteria	Belief degrees for evaluation grades				
		Best	Good	Fair	Poor	Worst
Hydrometeorology	Wind and wave	0	0	1	0	0
	Visibility	0	0	1	0	0
	Sea ice concentration	1	0	0	0	0
	Sea ice thickness	1	0	0	0	0
Channel	Channel depth	0	0	0.54	0.46	0
	Channel width	0	0.54	0.46	0	0
Traffic regulation	International regulation	0.07	0.71	0.12	0	0
	Domestic regulation	0.02	0.53	0.36	0	0
Navigation infrastructure	Icebreaker	0	0	0.33	0.59	0
	Port facilities	0	0	0.25	0.43	0.26
	Navigation facilities	0	0	0.26	0.62	0.04
	Nautical charts	0	0.24	0.41	0.27	0
	Acquisition of ice and hydrometeorological information	0	0.16	0.53	0.21	0

Table A-II

Evaluation results of all the environmental sub-criteria for the location of 'Tian You' in Kara Sea

Criteria	Sub-criteria	Belief degrees for evaluation grades

		Best	Good	Fair	Poor	Worst
Hydrometeorology	Wind and wave	0	1	0	0	0
	Visibility	0	1	0	0	0
	Sea ice concentration	0	0.96	0.04	0	0
	Sea ice thickness	0	0	0	0.97	0.03
Channel	Channel depth	0.04	0.96	0	0	0
	Channel width	0	1	0	0	0
Traffic regulation	International regulation	0.07	0.71	0.12	0	0
	Domestic regulation	0.05	0.46	0.42	0	0
Navigation infrastructure	Icebreaker	0	0.38	0.54	0	0
	Port facilities	0	0.44	0.47	0	0
	Navigation facilities	0	0.35	0.56	0	0
	Nautical charts	0	0.10	0.41	0.42	0
	Acquisition of ice and hydrometeorological information	0	0.18	0.53	0.21	0

Table A-III

The relevant weights and utilities in the sensitivity analysis for the weight of 'Hydrometeorology'

Weights				Average utilities		
Hydrometeorology	Channel	Traffic regulation	Navigation infrastructure	East Siberian Sea	Laptev Sea	Kara Sea
0.478	0.256	0.128	0.138	0.753	0.732	0.674
0.508	0.241	0.121	0.130	0.776	0.752	0.672
0.538	0.227	0.113	0.122	0.799	0.772	0.671
0.568	0.212	0.106	0.114	0.820	0.790	0.669
0.598	0.197	0.099	0.106	0.840	0.808	0.667
0.628	0.183	0.091	0.098	0.859	0.825	0.665

0.658	0.168	0.084	0.090	0.876	0.840	0.664
0.688	0.153	0.077	0.083	0.892	0.854	0.662
0.718	0.138	0.069	0.075	0.906	0.867	0.660
0.748	0.124	0.062	0.067	0.918	0.879	0.658
0.778	0.109	0.055	0.059	0.928	0.889	0.657
0.808	0.094	0.047	0.051	0.937	0.897	0.655
0.838	0.080	0.040	0.043	0.945	0.904	0.653
0.868	0.065	0.032	0.035	0.951	0.910	0.651
0.898	0.050	0.025	0.027	0.955	0.915	0.650
0.928	0.035	0.018	0.019	0.958	0.918	0.648
0.958	0.021	0.010	0.011	0.960	0.921	0.646
0.988	0.006	0.003	0.003	0.961	0.923	0.645

Table A-IV

The relevant weights and utilities in the sensitivity analysis for the weight of 'Channel'

Weights				Average utilities		
Channel	Hydrometeorology	Traffic regulation	Navigation infrastructure	East Siberian Sea	Laptev Sea	Kara Sea
0.256	0.478	0.128	0.138	0.753	0.732	0.674
0.286	0.459	0.123	0.132	0.734	0.715	0.678
0.316	0.439	0.118	0.127	0.714	0.697	0.683
0.346	0.420	0.113	0.121	0.693	0.679	0.688
0.376	0.401	0.107	0.116	0.672	0.660	0.693
0.406	0.382	0.102	0.110	0.650	0.642	0.698
0.436	0.362	0.097	0.105	0.629	0.623	0.703
0.466	0.343	0.092	0.099	0.607	0.605	0.708
0.496	0.324	0.087	0.094	0.586	0.587	0.713
0.526	0.304	0.082	0.088	0.565	0.569	0.718
0.556	0.285	0.076	0.082	0.545	0.553	0.722
0.586	0.266	0.071	0.077	0.526	0.537	0.727
0.616	0.247	0.066	0.071	0.508	0.523	0.731

0.646	0.227	0.061	0.066	0.491	0.509	0.734
0.676	0.208	0.056	0.060	0.476	0.497	0.738
0.706	0.189	0.051	0.055	0.463	0.486	0.741
0.736	0.170	0.045	0.049	0.450	0.477	0.744
0.766	0.150	0.040	0.043	0.440	0.469	0.746

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