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Arctic shipping risk management: A bibliometric analysis and a systematic review of risk influencing factors of navigational accidents

Shanshan Fu [a], Floris Goerlandt [b,*], Yongtao Xi [c]

[a] College of Transport & Communications, Shanghai Maritime University, Shanghai, China
[b] Department of Industrial Engineering, Dalhousie University, Halifax, NS, Canada
[c] Merchant Marine College, Shanghai Maritime University, Shanghai, China

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ABSTRACT

With the diminishing extents of Arctic sea ice, Arctic shipping becomes increasingly attractive for the shipping industry. Voyages along Arctic sea routes have seen a significant increase in recent years. Given the harsh environment, shipping operations in the Arctic constitute a hazardous activity for people onboard vessels, while vessels pose risks to vulnerable ecosystems and traditional socio-cultural environments. Given this emerging trend, this paper presents a bibliometric analysis of the broad academic literature related to risk management of Arctic shipping, published in the period from 2000 to 2019. Based on 221 articles, the bibliometric analyses provide insights in publication patterns concerning the year of publication, keywords, journals, and countries/regions from which the work originates. Furthermore, through a qualitative systematic review, this article presents a synthesis of risk influencing factors (RIFs) of navigational accidents in the Arctic, based on published quantitative risk models containing accident scenarios in Arctic shipping. To this effect, ten papers are investigated in detail, focusing on the scenario, methods, data sources, and RIFs. Identifying major thematic clusters in the RIFs, a model is proposed for synthesizing and illustrating the relationships among environmental and ship-related RIFs, and accident scenarios in Arctic shipping. A discussion is made concerning challenges in the research domain and future research directions, focusing on the strength of evidence in the risk models, the use of linear versus complex, systemic accident theories, and on the alignment of academic work with focus issues in regulatory contexts.

1. Introduction

In recent years, the diminishing extent of Arctic sea ice opens the Arctic sea routes for increasing periods of time, a trend that is expected to continue in the future (Barnhart et al., 2016; Ho, 2010). The North-East Passage (NEP) and North-West Passage (NWP) are the shortest sea routes connecting North-East Asia and the North/West Europe and North America (Meng et al., 2017; Schøyen and Bråthen, 2011; Theocharis et al., 2018; Zhang et al., 2019a). The shipping industry has become increasingly interested in prospects of navigating the Arctic due to possible benefits such as shorter voyage time and lower associated costs (Beveridge et al., 2016; Lasserre and Pelletier, 2011).

Consequently, the vessel movements along Arctic sea routes have seen a significant increase in recent years (Fu et al., 2016). According to the statistics data in the Northern Sea Route (NSR) Information Office (2019), the transit in NSR (passing through the NSR, and both departure and arrival ports are beyond the NSR) has increased from 2015 to 2018. In the North-West Passage, in Canadian waters there is destinational traffic to supply Northern communities and mining industries (Brooks and Frost, 2012), as well as transit traffic. Especially the tourism industries have experienced a remarkable growth in the area (Halliday et al., 2018), but economic uncertainties and concerns about

Abbreviations: BN, Bayesian Network; CFREF, Canada First Research Excellent Fund; DBN, Dynamic Bayesian Network; OOBN, Object-Oriented Bayesian Network; FSA, Formal Safety Assessment; ETA, Event Tree Analysis; FTA, Fault Tree Analysis; FETA, Fuzzy-Event Tree Analysis; FFTA, Fuzzy-Fault Tree Analysis; FMECA, Failure Mode, Effects and Criticality Analysis; FRAM, Functional Resonance Analysis Method; HFACS, Human Factors Analysis and Classification System; IMO, International Maritime Organization; NSFC, National Natural Science Foundation of China; NEP, North-East Passage; NSR, Northern Sea Route; NWP, North-West Passage; QRA, Quantitative Risk Assessment; RIF, Risk Influencing Factor; STAMP, System-Theoretic Accident Model and Processes; WoS, Web of Science.

* Corresponding author.
E-mail address: floris.goerlandt@dal.ca (F. Goerlandt).

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navigational safety and impacts to ecosystems and communities currently preclude Canadian Arctic transportation routes becoming major trade routes for commercial transit traffic (Lu et al., 2014). For similar reasons, also the NEP continues to account for a relatively small share of the total global commodity flows Meng et al. (2017). Nevertheless, the number of vessel movements is projected to increase in the future, for both the NEP and NWP (Council of Canadian Academies, 2017; Fu et al., 2016).

With the declining sea ice extent and the interest of the marine industries in operating in the area, Arctic shipping has become an emerging topic in the research related to the maritime transportation system. This has led to a sizeable body of literature, which in turn has been summarized in a series of review articles. Ford et al. (2012) discuss the effects of shipping development for vulnerability and adaptation in Arctic socio-economic systems by reviewing climate change in the Canadian Arctic from human dimensions. Jing et al. (2012) review ballast water management issues in harsh and Arctic environments. Lasserre (2014) discusses the profitability of the Arctic sea routes compared to traditional routes by reviewing 26 studies from 1991 to 2013. Meng et al. (2017) review the literature on Arctic shipping from the navigational and commercial perspectives, based on 25 articles. Dehghani-Sanij et al. (2017) review the sea spray icing studies on marine vessels and offshore structures in the Arctic and other cold regions. Ng et al. (2018) review the value and environmental feasibility of Arctic shipping from both physical and socio-economic perspectives. Theocharis et al. (2018) perform a review focusing on comparative studies between Arctic and traditional sea routes from 1980 to 2017, regarding both economic and environmental perspectives. Vergeynst et al. (2018) review biodegradation of marine oil spills in the Arctic from a Greenland perspective. Kujala et al. (2019) review the Arctic shipping studies from the perspective of risk-based design for ice-class ships. Zhang et al. (2019a) review the exploitation of trans-Arctic maritime transportation with a focus on remote sensing. Chan et al. (2018) perform a review focusing on invasive species in Arctic waters by shipping activities. Zhang et al. (2019b) discuss the solutions for reducing black carbon emissions in Arctic shipping from a policy perspective. Lavissière et al. (2020) investigation articles dealing with transportation and the Arctic using textometric approach.

These above-mentioned reviews focus on the feasibility of Arctic sea routes, on risk-based design and management of polar ships, and on the emission reduction in Arctic shipping. However, to the best of the authors' knowledge, there has not been any review of the literature on Arctic shipping with specific focus on risk management.

Nevertheless, risk management is a pertinent issue in maritime transportation, and a significant body of work has proposed models and approaches for identifying, analyzing, and evaluating risks to vessels and risk from vessels to the environment. Hetherington et al. (2006) provide an overview of work on human factors in maritime safety. Mazaheri et al. (2014) review ship grounding risk modelling, placing these in a risk management context and summarizing the factors considered in the models. Goerlandt and Montewka (2015) review the literature on waterway risk analysis with a focus on the conceptualization of risk and the underlying scientific commitments. Lim et al. (2018) review the work on maritime risk analysis, focusing on the types of models and computational algorithms applied in those. Chen et al. (2019a) perform a state-of-the-art review on probabilistic risk analysis of ship-ship collision. Luo and Shin (2019) review the literature on maritime accidents, applying a bibliometric analysis methodology, focusing inter alia on collaboration networks and publication trends in the research domain. Kulkarni et al. (2020) present a broad overview of prevention-oriented waterway risk management, with a Baltic Sea area focus. The significant number of review articles clearly shows that there is a large body of work related to risk and safety in the maritime domain. However, no comprehensive review of the literature addressing Arctic shipping risk management has been presented.

Due to the harsh environment in Arctic waters, risk management is also a significant issue for Arctic shipping. One reason for the need to focus on this is the occurrence of accidents in Arctic areas, which can lead to injuries and human casualties (Kum and Sahin, 2015). This signifies a need to focus work on measures to prevent accidents from occurring (Smith, 2019), including risk-based ship design (Bergström et al., 2016) well as work towards ensuring effective Search and Rescue response in case accidents occur (Drewniak and Dalaklis, 2018). Another reason is that Arctic shipping involves various risks to ecosystems on local, regional, and global scales. On a relatively local level, increased vessel traffic can for instance lead to risks to marine mammals due to increased shipping noise (Halliday et al., 2017) and due to vessel strikes (Elvin and Taggart, 2008). Risks with a potential to affect larger sea areas include for instance accidental oil spills (Nevalainen et al., 2018), which can have very significant ecosystem impacts and also negatively affect Northern communities socio-culturally (Afenyo et al., 2019). Finally, emissions of sulfur and nitrogen oxides from vessels induce risks to the Arctic ecosystem (Winther et al., 2014), while black carbon emissions can reduce the snow albedo, which increases heat absorption and hence can contribute to climate change on a global level (Zhang et al., 2019b).

Given the above, this study presents a review of the literature regarding risk management of Arctic shipping from 2000 to 2019. The objectives of the work are two-fold. First, the article gives broad insights in the literature on risk management of Arctic shipping using bibliometric analysis methods. Thus, insights in narrative clusters, research trends, collaboration networks, and influential journals in the research domain are obtained, similarly as in Hosseini et al. (2016), Luo and Shin (2019), Parkes (2012), Hulme et al. (2019), and Goerlandt et al. (2020). Second, a detailed qualitative systematic review method is applied, focusing on navigational accidents in Arctic shipping. Through a close inspection of quantitative risk analysis models for Arctic shipping operations, insights in accident scenarios and critical Risk Influencing Factors (RIFs) are obtained, similarly as in Mazaheri et al. (2014), Chen et al. (2019a), Ozturk and Cicek (2019), and Chen et al. (2019b).

The remainder of this article is organized as follows. Section 2 introduces the data collection procedure and the methods applied in the bibliometric analysis of Arctic shipping risk management and the systematic literature review and synthesis of RIFs in navigational accidents. Section 3 provides the results of the bibliometric analysis, answering the first research objective. Section 4 presents the systematic review of articles focusing on quantitative risk management (QRA) of Arctic shipping operations. Section 5 synthesizes the RIFs of Arctic shipping operations in a qualitative model. Section 6 presents a discussion focusing on accident scenarios, research trends, and future work. Section 7 provides concluding remarks.

2. Data collection procedure and methods for literature review

In this section, the data collection procedure and the methods used to obtain the results for the research objectives stated in the introduction, are introduced.

2.1. Data collection procedure

The data for this study were retrieved from the Web of Science (WoS) database, which is one of the largest multidisciplinary bibliographic information databases and is linked to a flexible content search platform. WoS is selected as a database, as it is generally considered one of the most comprehensive databases, with very high-quality information contents (Li et al., 2021). The WoS Core Collection: Citation Indexes (SCI-E and SSCI) databases were used to search original research articles and review papers related to risk management of Arctic shipping from 2000 to 2019. Articles from conference proceedings, editorials, and technical notes were not included in the search.

In bibliometric analyses and literature reviews, it is important to apply appropriate search criteria and strategies to ensure that the relevant literature is adequately covered (Wee and Banister, 2016). As an initial exploration of the literature, the terms “Arctic shipping” and “risk management” were selected as search criteria to identify the publications from WoS, but it was found that several highly relevant articles were not included in the search results. In order to make a comprehensive identification of the related publications, three topics were finally used to identify the publications related to risk management of Arctic shipping, using the following search strategy:

- topic 1: “Arctic”, and
- topic 2: “ship*” or “vessel*” or “maritime” or “icebreaker”, and
- topic 3: “safety” or “risk” or “security”.

The topic search means that the terms “Arctic” and “ship/vessel/maritime/icebreaker” and “safety/risk/security” are identified in the title, the abstract or in the keywords of the publications. It should be clarified that “ship*” refers to ship, ships or shipping, and that “vessel*” covers both vessel and vessels.

According to the above search criteria, and following a close reading of the abstracts of the obtained dataset to ensure relevance of the articles for the intended review scope, 221 publications (210 original research articles and 11 review articles) related to risk management of Arctic shipping were identified. Each publication in WoS contains the author, year, title, journal, keywords, abstract, subject categories, addresses of the authors, and references. These data of the 221 publications sorted in the WoS were exported for performing bibliometric analyses.

2.2. Methods for bibliometric analysis and qualitative systematic review

Bibliometric analysis is a method that relies on the visualization of quantitative information about a research domain, allowing researchers to obtain insights into specific aspects thereof. This can include thematic research clusters, collaboration networks, historic evolution patterns, and trends in the research focus areas (Li et al., 2021). The method has been used to obtain insights in several safety-related research domains, for instance domino effects in process industries (Li et al., 2017), safety culture (van Nunen et al., 2018), university laboratory safety (Yang et al., 2019b), and prevention-oriented waterway risk management (Kulkarni et al. 2020).

In the present work, apart from simple summary statistics, VOSviewer software is applied to perform the bibliometric analyses and visualizations. This software is one of the most popular methods in safety-related bibliometric analyses (Li et al., 2021). It implements the visualization of similarities technique (van Eck and Waltman, 2007, 2010), which draws clustered networks between data instances based on the level of similarity between these. Thus, it allows analyses such as the identification of co-citation networks, collaboration networks, and bibliographic coupling, which provide insights into the structure and development of the research domain, see e.g. Li et al. (2021) for further details. VOSviewer also contains a text mining and clustering module, which allows identifying thematic clusters of frequently occurring terms in the targeted research domain.

In this paper, the bibliometric analyses are performed on the dataset containing the 221 identified publications related to risk management of Arctic shipping. The methodological framework shown in Fig. 1 is adopted. This includes four aspects of analysis: (1) distribution by year of publication, (2) distribution by keyword, (3) distribution by journal, and (4) distribution by country.

VOSviewer is used to analyze and visualize the relationships between keyword and countries of the exported bibliographic data in text format, by co-occurrence and co-authorship analysis, respectively. In VOSviewer, a visualization map is composed of items, links, and clusters. Items represent a research object in the bibliographic data, and can represent keywords, authors, publications, or countries. Links represent the connection or relation between two items, with the width of the link associated with the link strength. Clusters are a set of interrelated items included in the visualization map. The statistics software IBM SPSS statistics 23 is used to analyze the distribution by year of publication and by journal, using the exported bibliographic data in excel format.

The qualitative systematic review of literature focusing on navigational accidents in Arctic shipping adopts a method as outlined by Grant and Booth (2009). The scope of this detailed analysis of the literature is limited to navigational accidents in Arctic shipping, i.e. accidents occurring due to the specific operational context of navigation in Arctic conditions. The specific aim is to develop a high-level qualitative synthesis of the evidence of which RIFs are associated with what accident types, with a focus on the factors leading up to the accident occurrence. Articles considered relevant for the current systematic review pertain to articles in which a quantitative risk analysis (QRA) of Arctic shipping is presented. To identify these articles, a close reading of the title and abstracts of the 221 identified articles is performed, similarly as in Kulkarni et al. (2020). The specific restriction to articles presenting QRA results is acceptable practice in qualitative systematic reviews as found by Grant and Booth (2009), and can be seen in context of building an

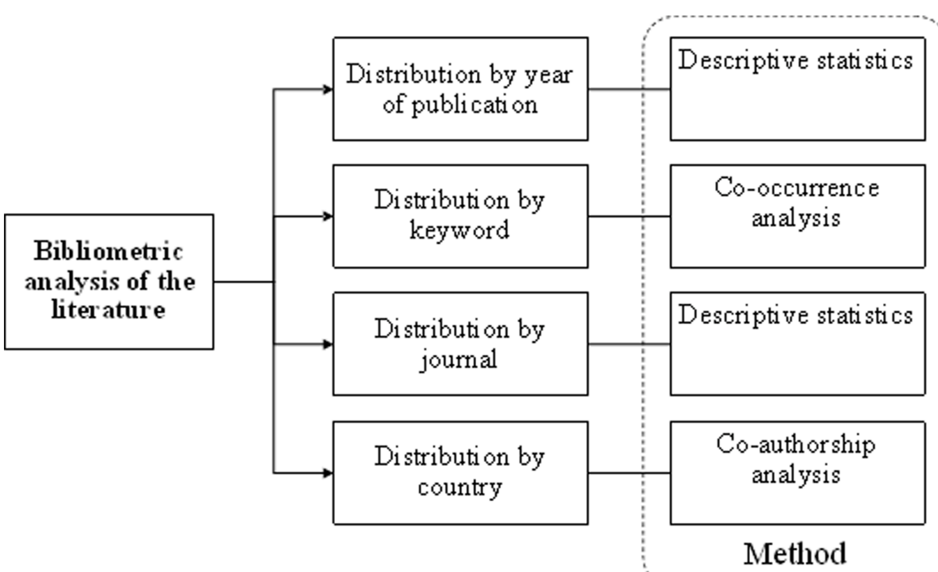

Fig. 1. Methodological framework for the bibliometric analyses of the literature related to risk management of Arctic shipping.

evidence synthesis for further improving risk analysis methods for navigational accidents in Arctic shipping. A similar approach is taken by Mazaheri et al. (2014) and Chen et al. (2019a) for developing grounding and collision accident risk models.

3. Bibliometric analysis of the literature

In this section, the selected 221 publications related to risk management of Arctic shipping are systematically investigated using bibliometric analyses focusing on the distribution by year of publication, keyword, journals, and countries or regions, as presented in Section 2.2.

3.1. Distribution by year of publication

The yearly distribution of the selected publications (articles and reviews) from 2000 to 2019, is presented in Fig. 2. Before 2007, it is evident that there was only very limited academic interest and focuses on Arctic shipping risk management. A marked increase occurred in 2008, with a more or less stable number of articles until 2013. Thereafter, the annual number of articles has increased rapidly, from 12 publications in 2014 to 41 publications in 2018. Moreover, the number of publications in the research domain remains high also in 2019 with 35 publications. Since 2012, review articles are emerging in the research domain on various topics, as outlined in the introduction.

3.2. Distribution by keyword

Co-occurrence analysis is used to analyze the keywords of the selected 221 publications related to risk management of Arctic shipping, using VOSviewer software. The keywords of the publications are represented as items, where the size of each item corresponds to the number of occurrences.

As shown in Fig. 3, 38 items are identified as critical keywords of the publications addressing risk management of Arctic shipping. All the keywords in the figure represent items with more than seven occurrences in the selected 221 publications. The most frequently occurring items are '*Arctic*' (60 occurrences) and '*climate change*' (46 occurrences), followed by '*sea ice*' (27 occurrences), '*risk*' (23) and '*Northern Sea Route*' and '*model*' (20 occurrences). The links between the items show the connections between the keywords in the publications, i.e., the figure shows which terms are commonly found together, where stronger links are represented by thicker lines. Using VOSviewer, these items are divided into three clusters, which represent terms which are stronger linked to one another than with terms in other clusters (van Eck and Waltman 2007). This additional clustering of these connected terms enables an expert interpretation of emerging narrative patterns in the research domain. Such interpretations are necessarily to an extent subjective, and hence subject to discussion, but they can be useful to get an indication of the major research themes in the considered problem domain (Li et al. 2021). For the results of Fig. 3, the authors, who are familiar with the research domain through earlier work in selected subareas within it, and through the data collection procedure explained in Section 2.1, provide a tentative indication of such narrative patterns as follows.

The publications of the red cluster in Fig. 3 can be considered to represent a plausible narrative pattern focusing on navigational risk analysis of Arctic shipping, the NSR or the other Arctic waters (e.g., Barents Sea, Alaska waters). The focus on navigation could be associated with a focus on work aimed at understanding the factors involved in navigational accident occurrence, especially for collision accidents. The publications of the green cluster in Fig. 3 can be understood to represent a narrative pattern addressing the impacts of climate change and sea ice on shipping, transport and ecosystems vulnerability, especially for the Arctic countries (e.g., Canada and Russia). The publications in the blue cluster of Fig. 3 seem to indicate a narrative pattern which focuses more on model-based risk assessment for ship operations or oil spill, in which Bayesian Network (BN) is the most mentioned analysis technique for risk assessment. As is common in bibliometric analysis (Li et al. 2021), there are some overlapping terms in the network and its clusters, e.g., risk analysis (red cluster) and risk assessment (blue cluster), which again indicates that the identified narrative patterns are primarily meant as a basis for discussion.

Fig. 4 shows the temporal trend of focus topics in the narrative patterns in risk management of Arctic shipping. Before 2015, publications focused on climate change-related analysis in Arctic regions. Recently, researchers have increasingly paid attention to risk analysis

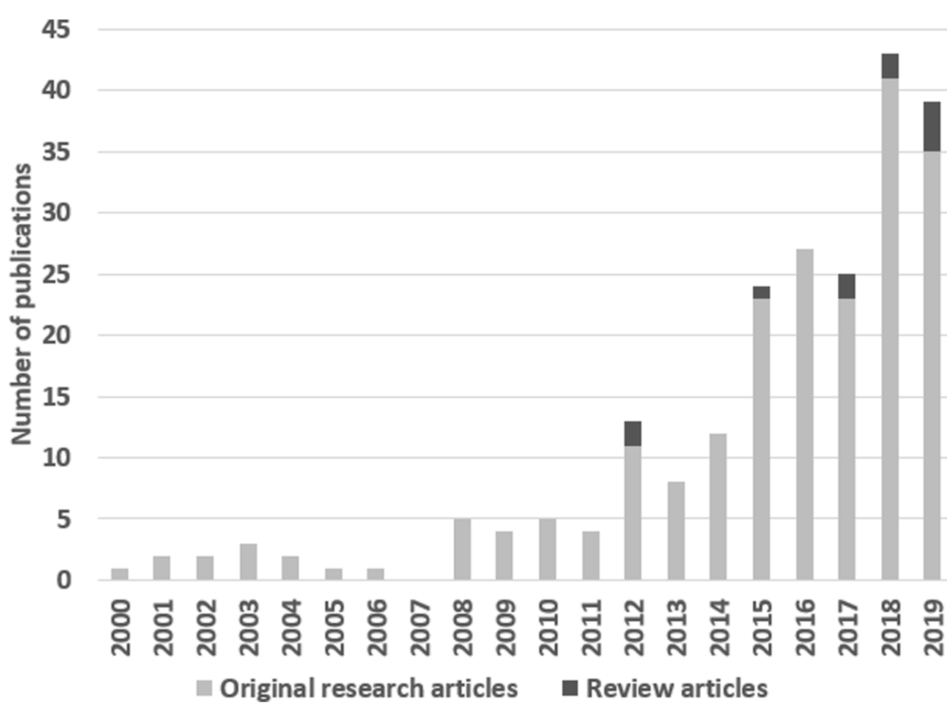

Fig. 2. Distribution of publications (articles and reviews) by year of publication from 2000 to 2019.

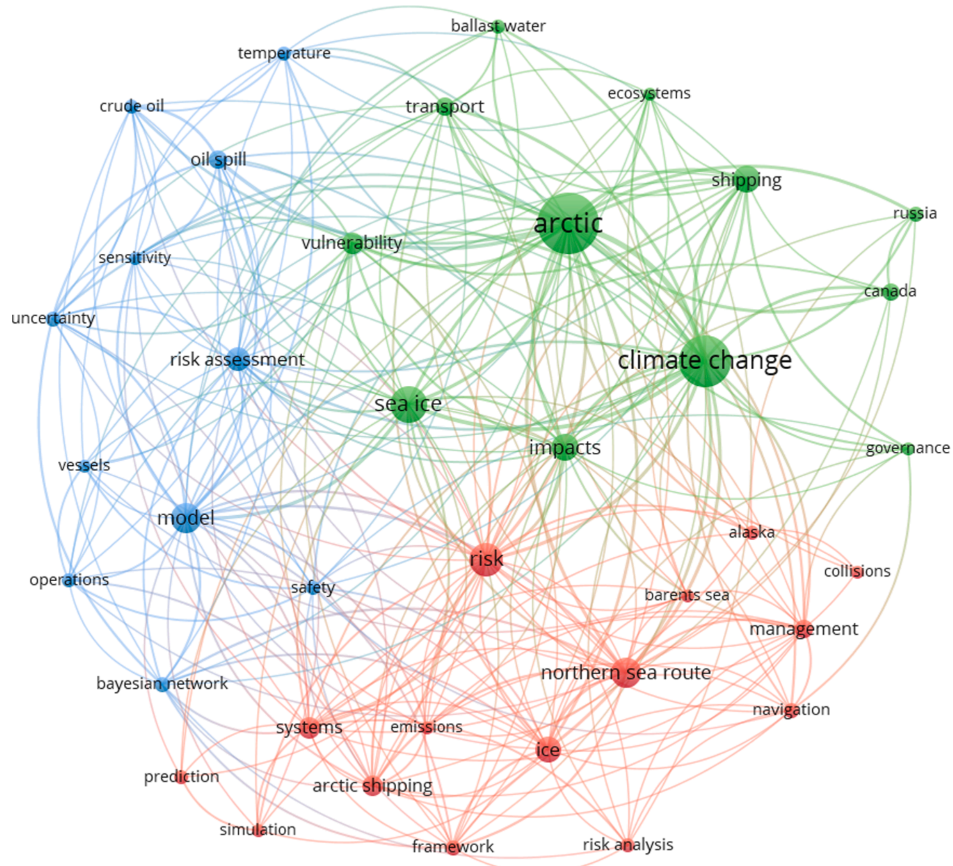

Fig. 3. Network visualization of co-occurrence analysis by keyword in the 221 publications related to risk management of Arctic shipping from 2000 to 2019, created by VOSviewer.

and assessment of Arctic shipping. Publications focused first on accidents in Arctic navigation, in which Bayesian Network modeling was a significant development. More recently, there is a focus on operations and oil spills, where uncertainty treatment, simulation modeling are significant topics related to model development.

3.3. Distribution by journal

The selected 221 publications related to risk management of Arctic shipping in the identified data sample were published in 129 different journals. Among these, 94 journals (72.9%) published only one article on the topic; 16 journals (12.4%) published two publications; while 19 journals (14.7%) published three or more publications. The wide distribution of the journals in which articles are published indicates that risk management is a very interdisciplinary research domain, which is approached by a variety of research communities with a common interest in Arctic shipping. It also shows that there are several journals with a more specialized focus on maritime transportation, Arctic areas, and risk management, which take a leading role in developing the research domain.

Table 1 lists the top 13 journals related to risk management of Arctic shipping, based on the number of publications in each journal. The table contains the number of publications on the research domain in these journals, and lists the subject category of the journal to give an idea of the types of research published in these journals in relation to Arctic shipping risk management. It is seen that there is a mixture of journals addressing environmental aspects, policy issues, engineering, oceanography, and operations research and management sciences.

As shown in Table 1, *Marine Policy*, *Ocean Engineering*, *Cold Regions Science and Technology*, *Marine Pollution Bulletin* are the most significant sources of publications related to risk management of Arctic shipping, with *Marine Structures*, *Maritime Policy & Management*, *Marine Technology Society Journal*, and *International Journal of Maritime Engineering* following. Most publications on risk modeling of Arctic shipping have been published in journals focusing on engineering and operations research and management science, in particular *Ocean Engineering*, *Safety Science* and *Reliability Engineering & System Safety*. Moreover, it is worth mentioning that *Marine Policy* journal has published a special issue on Arctic marine resource governance in 2016, which may explain why it is the top-ranked journal in the current analysis.

3.4. Distribution by country

Referring to Fig. 2, co-authorship analysis is used to map the cooperation among countries and regions for the 221 publications related to risk management of Arctic shipping from 2000 to 2019. The countries of the authors are represented as items, where the size of each item corresponds to the number of publications originating from each country. The links between these items denote the collaborations between countries, where the link width is associated with the intensity of collaboration. The selected 221 publications originate from 39 different countries or regions.

As shown in Fig. 5, 17 items are identified as the major countries contributing to research on risk management of Arctic shipping. These countries or regions had five or more publications on the topic. The most productive countries on the topic are Canada (71 publications), the United States of America (USA) (52 publications), Norway (40 publications), followed by England (22 publications), the People's Republic of China (17 publications), and Finland, Germany and Russia (15 publications). It is clear that countries with a direct stake in Arctic are the

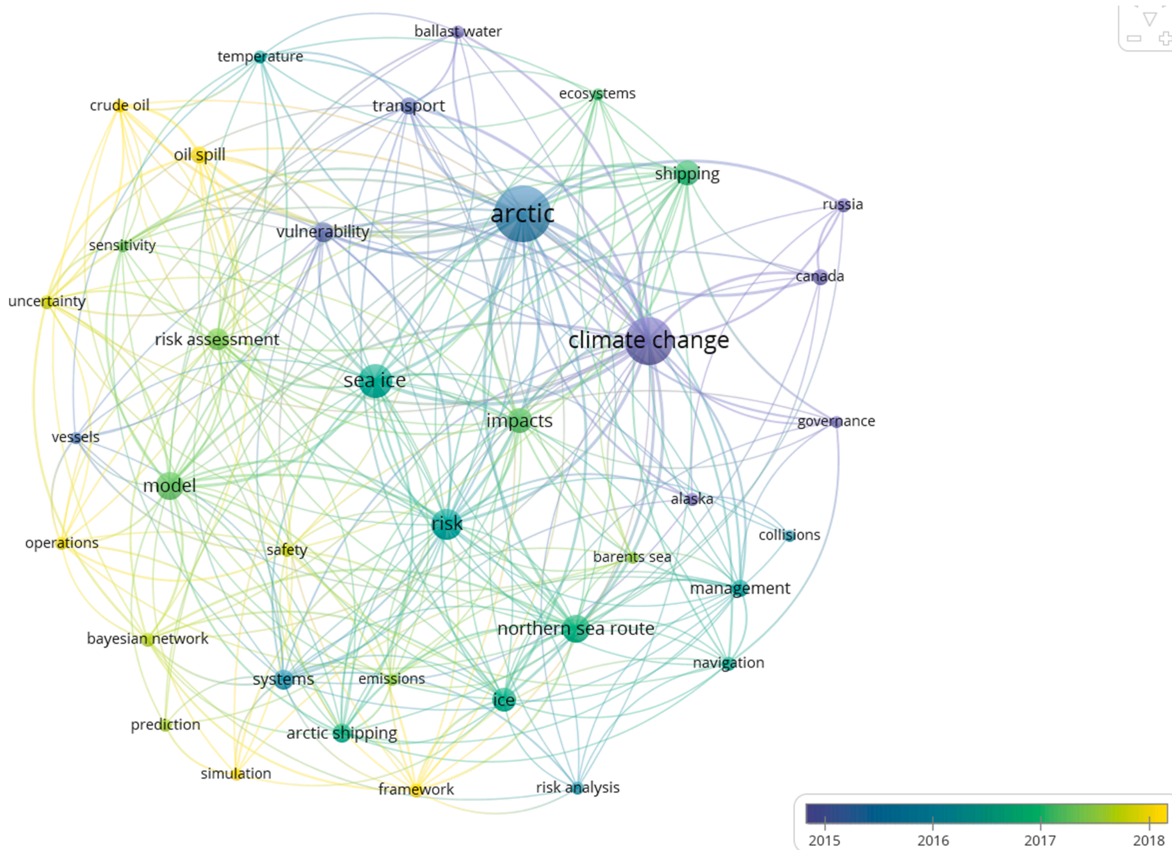

Fig. 4. Overlay visualization of the temporal evolution of keyword co-occurrence analysis in the 221 publications concerning risk management of Arctic shipping, colors represent average year in which the keywords appeared.

most productive in the research area. The most productive countries (Canada, USA, and Norway) have direct territorial-based stakes in Arctic developments. These are members of the Arctic Council, which is a high-level international forum addressing issues faced by Arctic littoral states in relation to safety, environmental protection, and sustainability of the Arctic area. Other productive countries or regions (England, Germany, People's Republic of China) have important economic interests in the global shipping economy, which may explain their interest in research on Arctic shipping risk management. The links between the nodes represent the existence and extent of collaborative research activities between the countries or regions, with thicker lines indicating stronger collaboration. The clustering of countries or regions indicates that collaborations between these entities in terms of activity in academic publishing are stronger than with entities from other clusters. While no very firm geographical conclusions can be made from this analysis, the green cluster indicates that North American countries (especially Canada and USA) work comparatively closely together, while the red cluster shows that many European countries collaborate, but overall on less intensive levels. In the blue cluster, The People's Republic of China has a somewhat stronger collaboration with Finland, but overall, the extent of system international collaboration is rather limited.

4. Review of papers in quantitative risk assessment

Based on the generic procedure outlined in Section 2.2, in this section, nine articles are further selected from the 221 publications from 2000 to 2019 in the dataset obtained as in Section 2.2, and one relevant latest article in 2020. As shown in Fig. 6, 44 publications are closely related to risk or accident analysis with the term "risk" or "accident" in the title or keywords, by perusing the 221 publications in the database. 25 publications are closely related to ship, shipping or marine analysis are identified by further getting through the database, with the term "ship*" or "marine" in the title or keywords. Among these 25 publications, most articles focus on qualitative analyses or discussions on risk factors or aspects of policy-making of Arctic shipping. Only ten papers present quantitative risk analysis models which explicitly include risk scenarios for navigational accidents leading up to the accident occurrence, including nine papers from 2000 to 2019 and one latest paper in 2020. Only these are considered further in the detailed inspection in the systematic review.

Hence, quantitative risk models focusing on the consequences of accidents, for instance the impacts on ecosystems (Nevalainen et al., 2017), socio-economic consequences (Afenyo et al., 2019) or the effectiveness of oil spill recovery operations (Lu et al., 2019; Shi et al., 2019), are not considered here. Only articles proposing risk models for navigational accident scenarios in Arctic shipping, such as collision, grounding, or ship besetting in ice, which include risk factors leading up to such an event, are included. While closely related, articles addressing winter navigation risks in non-Arctic areas, such as the winter navigation risk management model for ship navigation in the Northern Baltic Sea area by Valdez Banda et al. (2016), or data analyses of wintertime navigational accidents in the same area (Goerlandt et al., 2017; Montewka et al., 2015; Valdez Banda et al., 2015), are not included here either. This is because the traffic conditions (traffic volumes, ship types navigating in these areas), environmental conditions (only first year ice, compared to multi-year ice in the Arctic), and infrastructure supporting maritime transport in other sea areas with ice presence are often very different than in Arctic areas. To ensure a meaningful synthesis of evidence of RIFs of navigational accidents in the Arctic, the current scope restriction is considered necessary.

Table 2 presents selected analyzed aspects of the ten identified articles, with relevance for the scenario-based risk analysis of Artic

Table 1
Top journal source related to risk management of Arctic shipping from 2000 to 2019.

No.	Journal title	ISSN	No. of publications	Subject category of the journal*
1	Marine Policy	0308-597X	16	Environmental Sciences & Ecology; International Relations
2	Ocean Engineering	0029-8018	10	Engineering; Oceanography
3	Cold Regions Science and Technology	0165-232X	9	Engineering; Geology
4	Marine Pollution Bulletin	0025-326X	6	Environmental Sciences & Ecology; Marine & Freshwater Biology
5	Polar Record	0032-2474	6	Environmental Sciences & Ecology
6	Ocean & Coastal Management	0964-5691	5	Oceanography; Water Resources
7	Arctic	0004-0843	4	Environmental Sciences & Ecology; Physical Geography
8	Marine Technology Society Journal	0025-3324	4	Engineering; Oceanography
9	Marine Structures	0951-8339	3	Engineering
10	Maritime Policy & Management	0308-8839	3	Transportation
11	International Journal of Maritime Engineering	1479-8751	3	Engineering
12	Safety Science	0925-7535	3	Engineering; Operations Research & Management Science
13	Reliability Engineering & System Safety	0951-8320	3	Engineering; Operations Research & Management Science

*subject category of the journal was retrieved from the 2019 edition of Journal Citation Reports.

navigational accidents. Apart from a reference to the respective articles, the table includes the considered accident scenario(s), the high-level cluster of RIFs included in the model, the methods applied in the analysis and risk modeling, and the evidence sources for the development of the model and its quantification.

From Table 2, focusing on the considered accident scenarios in Arctic shipping, it is found that most papers address a single accident scenario, with only Aziz et al. (2019), Baksh et al. (2018) and Kum and Sahin (2015) considering multiple scenarios in their work. Baksh et al. (2018) integrated three accident scenarios in one risk model. Collision is the accident with most research attention, followed by models focusing on the risk of ship-ice impacts, ship-iceberg collision, and the event of a ship getting beset in ice.

Table 2 shows that RIFs extracted from the risk models are clustered in four main groups: environmental factors, ship-related factors, human factors, and organizational factors. All articles consider two or more of these types of RIF groups. Environmental and ship-related factors are the most commonly included RIFs in the risk models (Fu et al., 2018a,b; Khan et al., 2020; Kujala et al., 2019; Schröder et al., 2017; Song et al., 2016; Sulistiyono et al., 2015). However, it is known from other work on risk analysis of maritime transportation that also human and organizational factors have an important role in the accident occurrence (Aziz et al., 2019; El-Ladan and Turan, 2012; Graziano et al., 2016; Puisa et al., 2018; Schröder-Hinrichs et al., 2013; Uğurlu et al., 2018; Ung, 2018; Weng et al., 2019), which is also reflected in several risk models of Arctic shipping accidents. Nevertheless, only Kum and Sahin (2015) and Zhang et al. (2019c) present risk models where RIFs from all four clusters are included.

Focusing on the methods and modeling techniques used in the risk models, most of the work integrates several methods for the analysis and modeling. For instance, HFACS, FTA, ETA, fuzzy sets, and especially BN are frequently used. BN are popular modeling techniques for accidents in the maritime transportation system, see e.g. also Goerlandt and Montewka (2014), Hänninen and Kujala (2012), Hosseini and Barker (2016), and Montewka et al. (2017). For Arctic shipping risk modeling, half of the identified articles in Table 2 apply BNs (including DBN and OOBN) for accident scenario modelling, which is consistent with the results of bibliometric analysis in Figs. 4 and 5. FTA and ETA are also often used for accident scenario modeling in QRA, and sometimes fuzzy sets are incorporated and in the form of FFTA and FETA (Ferdous et al., 2011; Huang et al., 2001).

Table 2 shows as for the evidence sources applied in the quantitative risk modeling, most articles apply historical data available in the literature and expert judgment. It is noteworthy that mostly, the historical data does not directly originate from an Arctic shipping context, which may relate to scarcity of data and the difficulties in obtaining contents-rich accident data. This is a known problem even in more intensely navigated areas with more established data collection platforms (Harrald et al., 1998; Sormunen et al., 2016), and has been addressed in more detail for resource allocation problems in the Arctic (Fedi et al., 2018; Grabowski et al., 2016). Khan et al. (2020), Aziz et al. (2019), Zhang et al. (2019c), Fu et al. (2016), and Kum and Sahin (2015) use accident investigation reports or navigational data as part of the evidence base for the analysis and risk modeling of navigational accidents in Arctic shipping. Given the data paucity and difficulties in obtaining relevant information, most articles rely on expert judgment as evidence basis to develop risk models and/or to quantify the model parameters.

5. Risk influencing factors in navigational accidents in Arctic shipping: Analysis and synthesis

In this section, the RIFs considered in the QRA models for navigational accidents in Arctic shipping are analyzed in more detail. A brief comparison is also made between the critical RIFs in the ten papers and the International Maritime Organization (IMO) Polar Code (MSC, 2014). The Polar Code (MSC, 2014) lists ten hazard sources for ship operations in polar waters, which can be divided into three clusters, as follows:

- Environmental factors: ice, low temperature, extended periods of darkness or daylight, high latitude, remoteness and possible lack of accurate and complete hydrographic data and information, rapidly changing and severe weather conditions, sensitive environment,
- Ship-related factors: topside icing, lack of suitable emergency response equipment,
- Human and organizational factors: lack of ship crew experience in polar operations.

The comparative analysis of the RIFs in the risk models listed in Table 2 and the hazards in the Polar Code is made considering these three clusters, i.e., environmental, ship-related, and human and organizational factors.

5.1. Environmental factors

Table 3 presents an overview of the considered environmental RIFs in the selected ten articles on QRA of navigational accidents in Arctic shipping. The environmental RIFs are further split into four sub-categories (weather conditions, sea state, ice conditions, and other), and 19 root factors.

The ten identified articles consistently take several environmental factors into consideration. Almost all the articles applied at least three root RIFs from different sub-categories to develop risk models for accident scenarios in Arctic shipping except Aziz et al. (2019). Khan et al. (2018), Obisesan and Sriramula (2018) and Khan et al. (2020) consider ten, nine and eight root RIFs in their work, respectively. “Wind”, “visibility”, “drift/pack ice”, and “ridge ice/iceberg” are the most frequently

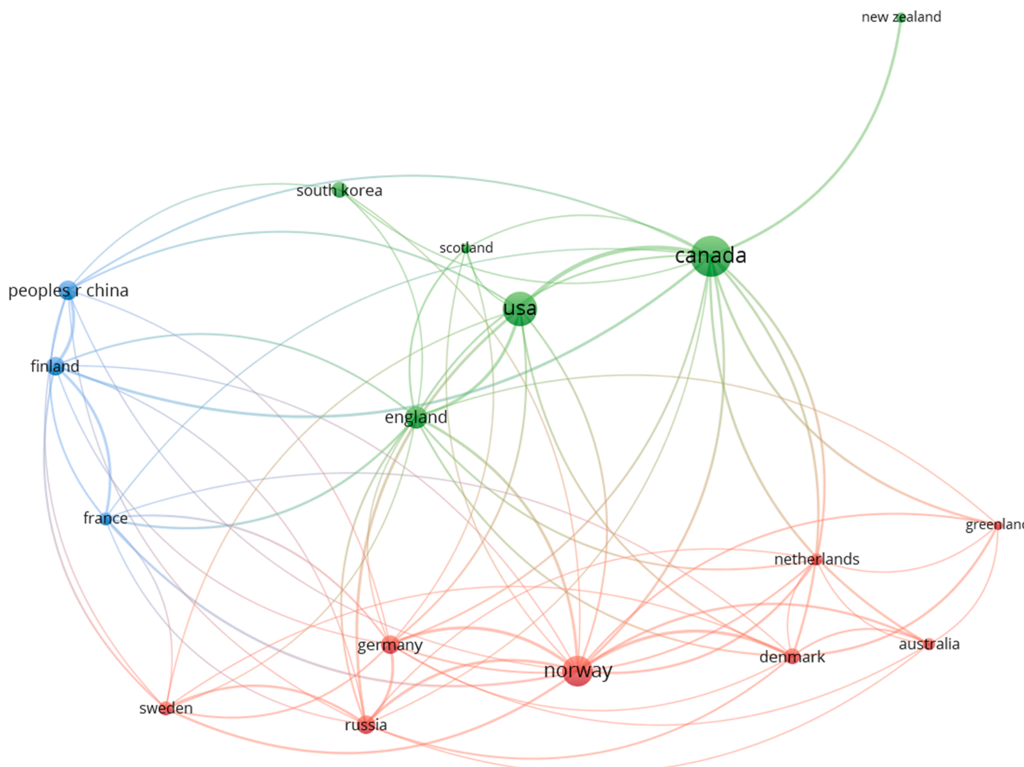

Fig. 5. Network visualization of co-authorship analysis by country in the 221 publications related to risk management of Arctic shipping from 2000 to 2019, created by VOSviewer.

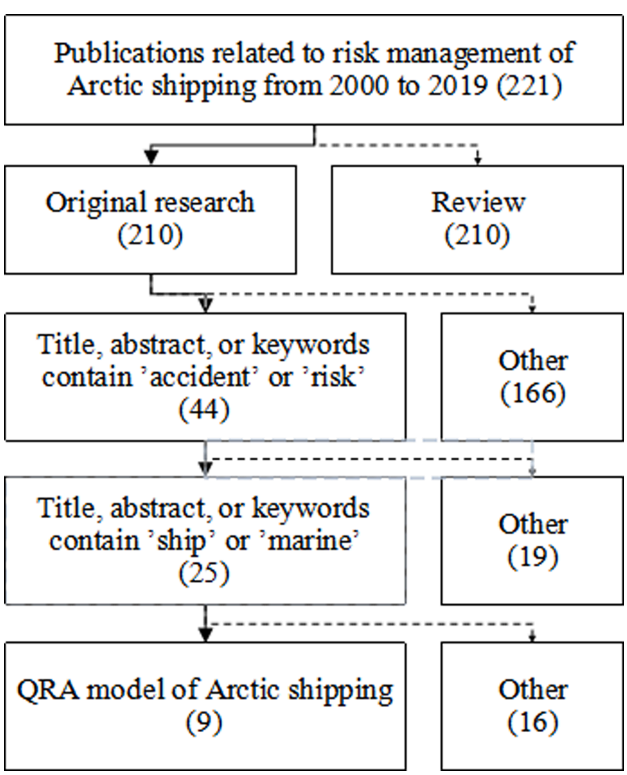

Fig. 6. Selection process of the 221 publications related to QRA of Arctic shipping from 2000 to 2019.

applied root RIFs, also identified as the critical environmental RIFs for navigational accidents in Arctic shipping, which are accounted for four or more times in the risk models. Wind and visibility are commonly identified RIFs in accident analyses in the maritime transportation system, see e.g., Rezaee et al. (2016), Luo and Shin (2019), and Ventikos et al. (2018). Ice conditions-related factors are special RIFs which are also considered in accident analyses and risk models for other sea areas in which sea ice affects ship navigation (Goerlandt et al., 2017; Valdez Banda et al., 2016), so it is unsurprising that these also appear in risk models for navigational accidents in Arctic shipping.

As mentioned in Section 4, only a few articles (Fu et al., 2016; Kum and Sahin, 2015; Zhang et al., 2019c) use accident data and/or accident reports as the evidence base for the risk model development, while the other articles rely on expert judgment or on assumptions. Considering this, it is apparent that the RIFs 'snow or rain', 'wind', 'visibility', 'low temperature', 'severe weather condition', 'wave', 'sea temperature', 'inadequate depth', 'ice concentration', 'ice thickness', 'drift/pack ice', 'ridge ice/iceberg', and 'impact from other ships' have a somewhat stronger evidence base than the other factors listed in Table 3, as these are based on empirical data. The other RIFs included in Table 3 are considered relevant by various experts (e.g., 'fog', 'sea current', or 'ice strength'), but are not as such based on empirical findings. Expert judgment is widely considered a relevant knowledge source in risk analysis contexts, but given the importance of considering uncertainties in the evidence base in contemporary risk perspectives (Aven, 2013; Goerlandt and Reniers, 2016; Zio, 2016; Zio and Aven, 2013), it is prudent to make distinctions between the strength of evidential support for different factors which are plausibly related to accident occurrence in Arctic navigation.

Comparing the risk factors in the risk models after with the hazard sources in the Polar Code, it is found that the articles use a more specific perspective than the Polar Code. For example, the articles apply five characteristics of ice: ice strength, ice concentration, ice thickness, drift/pack ice and ridge ice/iceberg, to specifically operationalize the hazard source 'ice' in the Polar Code. Most of the hazard sources identified in the Polar Code have been considered in these articles, only for 'sensitive environment' can an equivalent root RIF not be identified. This may be

Table 2
Aspects of papers addressing to quantitative risk analysis of Arctic shipping operations.

No	Reference	Scenario	RIF groups	Method	Evidence source
1	Khan et al. (2020)	Ship-ice collision	Environmental and ship-related factors	Dynamic Bayesian Network (DBN)	Ship navigation dataset, assumption data
2	Aziz et al. (2019)	Fire/explosion, machinery failure	Ship-related and human factors	Bow-tie (Fault Tree Analysis (FTA) & Event Tree Analysis (ETA))	Ship maintenance logbook, incident reports
3	Zhang et al. (2019c)	Collision (ship-icebreaker collision)	Environmental, ship-related, human and organizational factors	FTA, Human Factors Analysis and Classification System (HFACS)	Accident/incident investigation reports, expert judgment
4	Baksh et al. (2018)	Collision, foundering and grounding	Environmental, ship-related, and human factors	Bayesian Network	Literature and expert judgment
5	Fu et al. (2018a)	Ship stuck in ice	Environmental and ship-related factors	Fuzzy-Event Tree Analysis (FETA), Frank copula	Expert judgment
6	Khan et al. (2018)	Ship-ice collision	Environmental, ship-related, and human factors	Object-Oriented Bayesian Network (OOBN)	N/A (assumption data)
7	Obisesan and Sriramula (2018)	Ship-iceberg collision	Environmental, ship-related, and human factors	Efficient surrogate model, FTA	Literature
8	Afenyo et al. (2017)	Ship-iceberg collision	Environmental, ship-related, and human factors	Bayesian Network	Literature
9	Fu et al. (2016)	Ship stuck in ice	Environmental and ship-related factors	Correlation analysis, Bayesian Network	Ship navigation dataset, expert judgment
10	Kum and Sahin (2015)	Collision, grounding, machinery failure	Environmental, ship-related, human and organizational factors	Root cause analysis, current reality tree, Fuzzy-Fault Tree Analysis (FFTA)	Accident/incident investigation reports, expert judgment

Table 3
Environmental RIFs considered in the selected ten articles related to QRA of navigational accidents in Arctic shipping.

Environmental RIFs	1 Khan et al. (2020)	2 Aziz et al. (2019)	3 Zhang et al. (2019c)	4 Baksh et al. (2018)	5 Fu et al. (2018a)	6 Khan et al. (2018)	7 Obisesan and Sriramula (2018)	8 Afenyo et al. (2017)	9 Fu et al. (2016)	10 Kum and Sahin (2015)
Weather conditions										
Fog	√					√	√			
Snow or rain	√		√			√		√		
Wind				√		√	√	√	√	
Visibility	√		√			√	√	√	√	
low temperature	√								√	
Severe weather condition							√			√
Sea state										
Wave				√			√		√	
Sea current							√			
Sea temperature									√	
Inadequate depth					√					√
Environmental obstacles				√	√					
Ice conditions										
Ice strength	√					√				
Ice concentration	√							√	√	
Ice thickness						√			√	
Drift/pack ice	√			√	√	√	√			√
Ridge ice/iceberg			√	√	√	√	√	√		
Other										
Darkness	√					√				
Season						√				
Impact from other ships							√			√

explained because 'sensitive environment' is more associated with environmental consequences such as oil spill or noise pollution from vessels. The fact that the selected articles focus on factors contributing to the accident occurrence rather than on consequences, can explain that this factor identified in the Polar Code is not found in these articles in the academic literature.

5.2. Ship-related factors

Table 4 presents an overview of the considered ship-related RIFs in the selected ten articles on QRA of navigational accidents in Arctic shipping. The ship-related RIFs are further split into three sub-categories (navigability, machine failure, and other) and ten root factors.

Most of the articles consider three or more root RIFs from two or three different sub-categories, with Zhang et al. (2019c) and Baksh et al. (2018) accounting for six root RIFs. Following five root RIFs can be identified as the most significant factors, also the critical ship-related RIFs for navigational accidents in Arctic shipping, which are considered in three or more different risk models: 'ice class', 'engine power', 'ship speed', 'aids to navigation failure, limitation or errors', 'communication equipment failure' and 'icebreaker or tugboat failure'.

As indicated above, in the Polar Code only 'topside icing' and 'lack of suitable emergency response equipment' are listed as a hazard source related to ship-related factors. The articles thus consider more specific ship-related RIFs in the risk models, compared with the Polar Code. Failures of navigation aids and of communication equipment are

Table 4
Ship-related RIFs considered in the selected ten articles related to QRA of navigational accidents in Arctic shipping.

Ship-related RIFs	1 Khan et al. (2020)	2 Aziz et al. (2019)	3 Zhang et al. (2019c)	4 Baksh et al. (2018)	5 Fu et al. (2018a)	6 Khan et al. (2018)	7 Obisesan and Sriramula (2018)	8 Afenyo et al. (2017)	9 Fu et al. (2016)	10 Kum and Sahin (2015)
Navigability										
Ice class			√			√			√	
Engine power		√	√						√	
Ship speed	√		√			√	√	√	√	
Structural failure				√						
Machinery failure										
Power failure (steering/propeller/ bow thruster)		√	√	√				√		√
Aids to navigation failure, limitation or errors (radar/ navigator/anti-collision/ ECDIS)				√		√	√	√		√
Communication equipment failure			√	√	√	√		√		√
Structural failure				√						
Other										
Icebreaker or tugboat failure			√	√			√			√
Distance between two ships		√	√							

commonly applied RIFs in maritime accidents in various waters, see e.g. Hänninen and Kujala (2012) and Sotiralis et al. (2016). Ice class and icebreaker or tugboat failure are special RIFs in Arctic shipping accidents, and are included also in other risk models for navigation in ice-covered waters (Valdez Banda et al., 2016) or in a risk-based design context for vessels operating in ice conditions (Kujala et al., 2019).

As noted in Section 4 and Section 5.1, it is worth noting that only the work by Aziz et al. (2019), Kum and Sahin (2015) and Zhang et al. (2019c) are based explicitly on accident data and/or accident reports. Hence, it can be argued that the RIFs applied in these articles have a somewhat stronger evidence base than the RIFs which are based solely on expert judgment, which is important to be aware of in a risk analysis context (Aven, 2013; Goerlandt and Reniers, 2016). These data-based RIFs are 'ice class', 'engine power', 'ship speed', 'power failure (steering/propeller/bow thruster)', 'communication equipment failure', 'aids to navigation failure, limitation, or errors (radar/navigator/anti-collision/ECDIS)', 'icebreaker or tugboat failure', and 'distance between two ships'.

The hazard source identified in the Polar Code – 'topside icing' have not been considered in these articles, which may be explained because 'topside icing' is more readily linked to occupational accidents and stability-related accident, rather than navigational accidents. The fact that the selected articles focus on factors contributing to the accident occurrence rather than on consequences, can explain that this factor identified in the Polar Code is not found in these articles in the academic literature.

5.3. Human and organizational factors

Table 5 presents an overview of the considered human and organizational RIFs in the selected ten articles on QRA of navigational accidents in Arctic shipping. The human and organizational RIFs are furthers split into two subcategories (human and organizational), and 11 root factors.

Half of the identified articles consider three or more root RIFs from two different sub-categories. Zhang et al. (2019c) and Khan et al. (2018)

Table 5
Human and organizational RIFs considered in the selected ten articles related to QRA of navigational accidents in Arctic shipping.

Human and Organizational RIFs	1 Khan et al. (2020)	2 Aziz et al. (2019)	3 Zhang et al. (2019c)	4 Baksh et al. (2018)	5 Fu et al. (2018a)	6 Khan et al. (2018)	7 Obisesan and Sriramula (2018)	8 Afenyo et al. (2017)	9 Fu et al. (2016)	10 Kum and Sahin (2015)
Human										
Fatigue						√				
Negligence			√					√		
Lack of situational awareness			√							√
Inadequate knowledge (hardware/software/ technique)						√		√		
Judgment or decision failures			√			√				
Human error/failure		√		√			√			
Organizational										
Insufficient tugboat use				√						
Anti-collision rule gap			√							
Charts and publications updating				√						
Safety measure and preventive action (Lack/ inadequate)			√			√				
Lack of communication or miscommunication			√			√		√		√

consider seven and six root RIFs in their presented risk models, respectively. The most critical root factor is 'lack of communication or miscommunication', in the sense that it is considered most frequently in the different risk models, namely four times.

Comparing the RIFs in the risk models with the hazard sources in the Polar Code, it is found that in the Polar Code only one hazard source (lack of ship crew experience in polar operations), is listed. It is a subjective factor, which is difficult to evaluate and quantify. None of the articles use this factor directly in the risk modeling, but some analogous and arguably more specific factors are used, such as 'inadequate knowledge' or 'judgment or decision failures'.

Considering the strength of evidence of these human and organizational RIFs, as mentioned in Section 4, and Sections 5.1 and 5.2 above, it is noted that only the models by Aziz et al. (2019), Zhang et al. (2019c) and Kum and Sahin (2015) are based on accident data and/or reports. Hence, it can be argued that the factors identified in those models have a somewhat stronger evidential basis than the other factors, even though the others are also plausible as they have been identified based on expert judgment. These data-based factors are: 'negligence', 'lack of situational awareness', 'judgment or decision failure', 'anti-collision rule gap', 'safety measure and preventive action (lack/inadequate)', and 'lack of communication or miscommunication'.

5.4. Synthesis: A model for RIFs and navigational accident scenarios in Arctic shipping

The analysis of RIFs for navigational accidents in Arctic shipping in the previous sections shows that environmental, ship-related, and human and organizational factors are considered in the various risk models of navigational accident scenarios in Arctic shipping. The RIFs in different accident scenario have some differences. Based on the analyses presented in Section 4 and Sections 5.1 and 5.2, a mapping of the RIFs considered in the ten articles for the different accident scenarios is presented in Fig. 7. The qualitative model illustrates and synthesizes the relations between environmental and ship-related RIFs and the accident scenarios for the different navigational accident types.

The model presents the relationship between four critical environmental RIFs, five critical ship-related RIFs, and four navigational accident scenarios. These relationships can be used as a basis for identifying risk control options and risk management strategies for ship collision, grounding, stuck in ice, and ship-ice/iceberg collision scenarios. The analysis in Section 5.3 shows that human and organizational factors are also considered in some publications for risk management of Arctic shipping navigational accidents. However, as the identification and selection of these factors are strongly dependent on the accident theory used as reference in the data analysis, as further discussed in Section 6, and because of the relatively poor data on which the identification of these factors is based, human and organizational factors are not considered in this synthesis. Even though human and organizational factors are important in accidents in the maritime transportation and in navigational accidents in Arctic shipping, there is high uncertainty about how exactly human operators and their organizational context are associated with accidents. This is an important area of future research.

6. Discussion

The review of publications related to risk management of Arctic shipping presented in Section 3 allows insights in the development of the research domain. The review, analysis, and synthesis of articles addressing quantitative risk analysis for Arctic shipping navigational accidents in Section 4 and Section 5 has provided insights in the considered accident scenarios and RIFs. In this section, some further issues relevant to the development of this research domain are briefly discussed.

The analysis and synthesis of the articles focusing on quantitative risk analysis shows that the risk models are built on relatively little empirical accident data or accident reports. This is understandable, given the low traffic volumes in Arctic areas (Yang et al., 2019a), and because of the low accident rates of shipping in general (AGCS, 2019). The reliance on expert judgment in the risk models is understandable from that point of view, acknowledging that expert judgment is very common in risk analysis (O'Hagan et al., 2006; Meyer and Reniers, 2016; Zio and Aven, 2013). However, care should be taken not to overly rely on the RIFs based on expert judgments. A first reason for this is that various risk models identified in Section 4 often include different RIFs. This means that there is no conclusive agreement between experts on what factors are involved in accident causation, although some patterns can be suggested as in Section 5.4. These disagreements between expert judgments signify a relatively low strength of evidence, which is important to consider when making judgments concerning risk control options or risk management strategies (Aven, 2013). Second, the general literature on the validity of expert judgments in risk analysis warns that

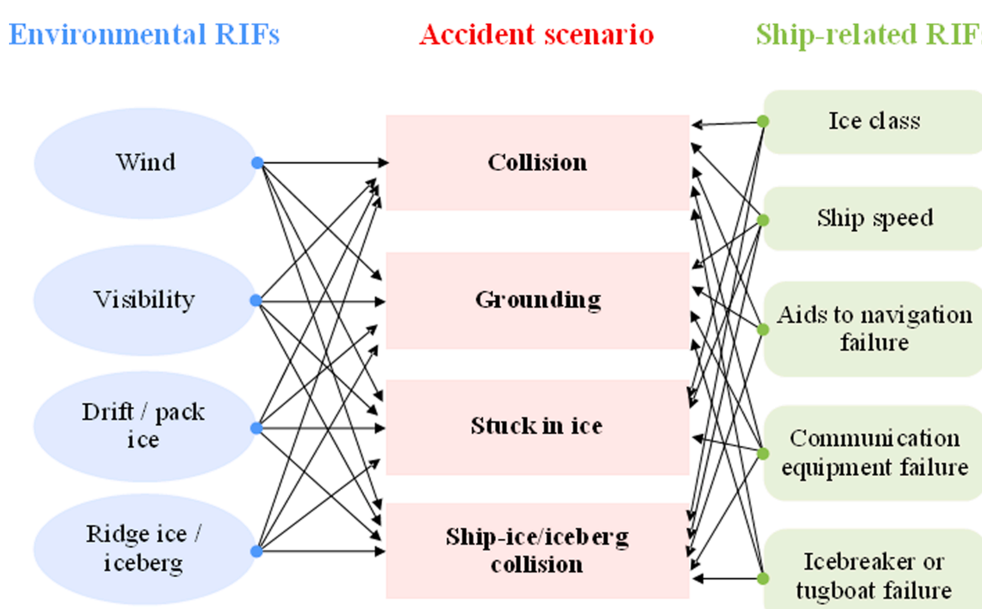

Fig. 7. A model for the relationship among environmental and ship-related RIFs and navigational accident scenarios in Arctic shipping.

only well-understood local causal mechanisms can confidently be taken to have special epistemic standing (Rae and Alexander, 2017; Zio and Aven, 2013). It is doubtful in how far the causation mechanisms of Arctic shipping accidents can be considered such well-understood local causal mechanisms, because of the relative lack of experience with Arctic shipping and especially with accidents in Arctic conditions. Moreover, it is known from the wider literature on maritime accident analysis that the focus typically is on proximate factors close in time and space to the accident occurrence. More distal factors, such as organizational and human factors, are less frequently identified (Chen et al., 2013; Puisa et al., 2018; Schröder-Hinrichs et al., 2011). These uncertainties about the significance and relative importance of varying RIFs are important to consider when relying on the results of this literature for risk management and decision-making.

Another issue is the modeling techniques applied in risk modeling. As found in Section 3.2, BN is the most frequently applied modeling techniques in the research domain. Focusing on the quantitative risk models in Section 4, modeling techniques such as FTA and BN are most prevalent. BN is very flexible tool which can easily implement complex interdependencies between RIFs, are very well suited to incorporate various types of evidence (data, expert judgments, model results), and can handle epistemic uncertainties in a coherent manner. Even though BN is frequently used in maritime accident modeling (Zhang and Thai, 2016), they are conceptually limited for modeling accident causation as they cannot implement feedback mechanisms which are inherent in modern systemic accident theories in complex socio-technical systems (Hänninen, 2014). Relatively recently, non-linear accident theories have been applied for risk management in the maritime domain (Hulme et al., 2019), for instance the System-Theoretic Accident Model and Processes (STAMP) (Leveson, 2004; Leveson, 2011) and the Functional Resonance Analysis Method (FRAM) (Hollnagel, 2012), see for example Valdez Banda et al. (2019), Lee and Chung (2018), Valdez Banda and Goerlandt (2018), and Praetorius et al. (2016). Also, in the context of Arctic shipping risk management, such non-linear accident theories have been explored as well, see e.g. Smith (2019) using the FRAM model to understand Arctic ship navigation and build the complex human-technical relationships in the Exxon Valdez grounding accident. Furthermore, along with the more data enriching the maritime accident database, data-driven approaches are applied in risk management of maritime accidents, for instance Tree Augmented Naive Bayes (TAN) classifier and Ordered Probit model, see e.g. Wang et al. (2019) and Weng et al. (2018). Future work in non-linear and data-driven approaches for maritime risk management would be worthwhile.

A final note can be made about the alignment of the research domain on risk management of Arctic shipping with regulatory focus issues at the level of the IMO. Earlier work by Schröder-Hinrichs et al. (2013) has concluded that no relationship could be identified between topics addressed in journal publications and issues addressed in IMO documents. Also, there is lack of consideration of Polar Code for risk management of Arctic shipping risk in published work. Relatively recently work by Fedi et al. (2018, 2020) has analyzed the Polar Code contributions to risk management of Arctic shipping, but it has only limited capacity to evaluate navigational risks in Arctic shipping. The current work does not specifically focus on this issue, but it would be interesting to ascertain the extent to which the two areas of activity are interconnected. Such knowledge could possibly be used to further strengthen the use of scientific evidence in policy contexts, and to entice applied academic work to more directly align with information needs and uncertainties in policy environments. This is therefore also recommended as future work.

7. Conclusions

In context of the growing interest in Arctic shipping, this article has presented a systematic review of the literature on risk management of Arctic shipping from 2000 to 2019. 221 publications are investigated using bibliometric analyses, focusing on the development of the research domain through the distribution by year of publication, the narrative clusters based on article keywords, the main journals advancing the knowledge in this area, and the countries or regions contributing most significantly.

The article also presents a synthesis of the research contributions focusing on quantitative risk assessment of navigational accidents in Arctic shipping, where accident scenarios and especially Risk Influencing Factors (RIFs) have been in focus. Ten articles focusing on risk modeling are retrieved and analyzed, focusing on the accident scenarios considered, the methods and modeling techniques applied, the evidence sources based on which the risk models are developed, and the RIFs included in these. Based on the analysis, a hierarchical model is proposed as synthesis to illustrate the relationships among environmental and ship-related RIFs and accident scenarios in Arctic shipping. These relationships provide insights in the factors involved in the navigational accident scenarios in Arctic shipping, namely collision, grounding, stuck in ice, and ship-ice/iceberg collision, which may useful as a basis for identifying risk control options and developing management strategies.

Even though the quantitative risk models for Arctic shipping provide insights in accident scenarios and RIFs, it is important to note that the evidence base of many of these is relatively weak. Expert judgment is commonly applied in the literature, due to the scarcity of accident data and the challenges in obtaining this. While expert judgment is commonly applied in risk analysis, and while experts in different articles identify many common RIFs, the relatively weak evidence underlying the risk models should be carefully considered when proposing or implementing risk control options based on the identified literature.

It is also noteworthy that the risk models and their underlying evidence are based on linear accident causation models, such as the Human Factors Analysis and Classification System (HFACS), Fault Tree Analysis (FTA), and Bayesian Networks (BNs). There are some developments in the research area which consider more modern systemic accident theories as a basis for Arctic shipping risk management. This line of research may be fruitful to pursue further in future research. Other future research could focus on field work, to build a systematic understanding of challenges in Arctic navigation based on empirical grounds. This could focus on the clusters of RIFs identified in the presented synthesis, i.e. environmental factors, ship-related factors, and human and organizational factors. Modeling techniques such as structural equation modeling and discrete choice modeling could be applied in future work to analyze and synthesize human attitude and behavior in Arctic shipping risk management. Finally, it is also apparent that the academic work on risk management of Arctic shipping is often not very well aligned with the discussions and focal issues at the level of the International Maritime Organization. It may be worthwhile to close this gap between academic work and policy environments in future work.

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