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On risk management of shipping system in ice-covered waters: Review, analysis and toolbox based on an eight-year polar project

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ABSTRACT

With the climate change, polar sea ice is diminishing. This, on one hand, enables the possibility for e.g., Arctic shipping and relevant resource exploitation activities, but on the other hand brings additional risks induced by these activities. Increasing research focuses have been observed on the relevant topics in the complex and harsh polar environment and its fragile ecosystem. However, from risk management perspective, there is still a lack of holistic analysis and understanding towards safe shipping in the ice-covered waters and its available models applicable for managing risks in the system. Therefore, this paper aims to establish a framework and analysis for better understanding of this gap. The paper targets a comprehensive and long-term project specifically focusing on holistic safe shipping in ice-covered waters as the analysis basis. It firstly creates a holistic framework for the shipping system in ice-covered waters and then implements review and analysis of project publications on their overall features. Quantitative prediction models are selected for a structured applicability analysis. Furthermore, an extensive review outside the project following the elements established for the holistic shipping system is conducted so that this paper provides an overview of models for the shipping system in ice-covered waters, addressing the status of the current toolbox. Moreover, it helps to identify the next scientific steps on risk management of shipping in ice-covered waters.

1. Introduction

With the climate change, polar sea ice is diminishing, and the polar sea is more opening than the previous. This attracts more attentions on potential activities including resource exploitation and shipping via its shorter routes e.g., in the Arctic Sea. However, the increasing shipping and activities in the in ice-covered waters are likely to increase corresponding risks and the consequences could be severe due to the remote, complex and harsh polar environment. Therefore, it becomes vital to understand more about the risk analysis and risk management of shipping in ice-covered waters.

A marked amount of research has been carried out recently to study the relevant topics in the shipping system in ice-covered waters. This in turn also generates a series of review articles. There are different review perspectives, e.g., Lasserre (2014) compared the profitability modelling of the Arctic shipping routes based on research from 1991 to 2013. Meng et al. (2017) reviewed the viability of transarctic shipping routes from the navigational and commercial perspectives. Theocharis et al. (2018) implemented a systematic literature review to assess the extant literature on comparative studies between Arctic and traditional routes from both economic and environmental perspectives. Afenyo et al. (2016b) performed a review of fate and transport of oil spills in open and ice-covered water and Vergeynst et al. (2018) reviewed biodegradation of marine oil spills in the Arctic from a Greenland perspective. Kujala et al. (2019) conducted a review from the perspective of risk-based design for ice-class ships. Lavissière et al. (2020) carried out a systematic literature review on transportation systems in the Arctic using textometry, where risk management is identified as a major area for further investigation. Xu et al. (2021) started a review of risk analysis models applied within shipping in ice-covered waters and Fu et al. (2021) implemented a bibliometric analysis and a systematic review of risk influencing factors of navigational accidents for Arctic shipping. Increasing risk approaches can be seen to be involved in recent reviews. However, the reviews focus more on navigation models, which is only a part of the shipping system for ice-covered waters. Therefore, there is still a lack of review and analysis on holistic shipping system in ice-covered waters. In addition, there is no systematic reviews or foundations focusing on the available models (toolbox) for practical risk

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management in ice-covered waters.

The regulations, e.g., International Code for Ships Operating in Polar Waters (Polar Code) came into place to ensure safe polar navigations and reduce the risks. However, in the practical management of the risks relating the shipping in ice, it is still not very clear what are the potential models or tools applicable for managing the risks which may occur inside the system, and where the models are immature or lacking. In 2017, the Emergency Prevention, Preparedness and Response Working Group (EPPR) of the Arctic Council identified a need for a common approach to marine risk assessments in the Arctic region and together with the Norwegian Coastal Administration (NCA) and Det Norske Veritas (DNV) carried out the work to screen methodologies, tools, and data to develop a Guideline. The guideline for Arctic marine risk assessment established a good structure for such a topic following the risk management process in ISO 31000:2018. However, it also has some limitation on including the emerging and applicable models/tools for various risks specifically for the shipping system in ice-covered waters. Therefore, a specific toolbox for the ice-covered waters risk management needs more inputs and analysis, such as the summary and analysis work done in OpenRisk project (HELCOM, 2018) for the open sea conditions. Considering all above, this paper aims to contribute to holistic analysis and understanding towards safe shipping in ice-covered waters and its available toolbox applicable for covering comprehensive elements in the system.

In order to have a holistic perspective and elements for the shipping system, the paper targets a comprehensive and long-term project specifically focusing on holistic safe polar shipping as the analysis basis. The long-term project has coherent focus and involves fundamental elements and holistic views towards safe polar shipping, thus provides a good basis for analysis. The polar project has two stages namely CEARCTIC (Centre of Excellence for Arctic Shipping and Operations) and CEPOLAR (Centre of Excellence for Scenario-based Risk Management in Polar Waters) starting from 2013 to 2022 focusing on different aspects regarding safe shipping in ice-covered waters. It is funded by Lloyd's Register Foundation and combines the research strengths from five universities: Aalto University, Hamburg University of Technology, Memorial University of Newfoundland, Norwegian University of Science and Technology and University of Helsinki. Extensive research work has been carried out in the framework of risk management towards safe shipping and the outcomes are mainly published in scientific journal and conference papers, where various subjects, research directions and methods have been focused and applied.

Therefore, the paper establishes a holistic framework for shipping system in ice-covered waters and takes the review and analyze of the research work carried out within the eight year project as the first step to have a deeper overall understanding of the research outcomes and trends. Then the next focus moves to the quantatitive prediction models to form a potential applicable toolbox for practical risk management of shipping in ice-covered waters. Relevant applicability analysis are conducted in terms of various features to assess the applicability level of the models. To further supplement the toolbox, an additional review is carried out for papers outside the project so that the relevant quantitative models can be employed to enrich the toolbox. This also enables to show the potential gaps on models for risk management of shipping in ice-covered waters.

The following sections are arranged as below. Section 2 describes the overall methodology. Section 3 presents the corresponding results and discussion. Section 4 concludes.

2. Methodology

2.1. Framework of review and analysis

In order to have a comprehensive review and analysis on the research carried out within the project, a general framework is needed. Considering the shipping in ice-covered waters as a holistic system, a framework in the system based on sub-system appearance and impact sequence is proposed as shown in Fig. 1. The strating element for the system naturally comes to *Ice*. When ice is present, its impact comes. Thus, the second topic element is defined as *Ice impact*. Under impacts from ice, *Hazardous event* comes next. Following that, *Oil outflow* can happen or even *Loss of vessel* as a outcome of hazardous event. If oil spill happens, *Weathering and transport of oil* will happen, as well as its corresponding *Response and recovery*. The situations of oil and corresponding response and recovery affect the ecosystem, defined as *Ecosystem impact*. Meanwhile, if loss of vessel occurs, *Evacuation and rescue* are needed. And all these, including ecosystem impact, response and recovery, evacuation and rescue, have *Economic impact,* as well as *Health impact,* and then *Socio-cultural impact*. When linking these elements in time and impact sequences under the icy environment, they constitue a holistic framework for shipping in ice-covered waters as described in Fig. 1.

Following the framework, the review and analysis on CEARCTIC and CEPOLAR are carried out. Four main features are determined to be investigated into the publications, corresponding to four practical questions:

1) what is studied – research topic;
2) what method is utilized – research method;
3) what is the overall practical purpose – practical utilization purpose;
4) where it can be applied in risk management - risk governace framework.

The first two questions relate to reviewing and understanding the research work conducted and the rest two questions try to form the links between the research and practical risk governace, which will be useful for the next step, i.e. the applicability analysis for models in terms of risk management of shipping in ice-covered waters. The methods for guiding the four research questions are further illustrated below.

2.1.1. Research topic

Research topics generally follow the elemants within the framework in Fig. 1. Therefore, the first topic is ***Ice***, which can be further divided in detail into sub-topics, referred as *Ice modelling* and *Ice condition* as shown in Table 1. The second topic is defined as ***Ice impact***, including *Ice loading*, *Ice resistance* and *Transportation system in ice* as sub-topics. ***Hazardous event*** comes as the third topic, including *Ship besetting/delay*, *Ship-ice collision*, *Ship-ship collision/grounding*, and *Hull damage* as sub-topics. ***Oil outflow*** and ***Loss of vessel*** are referred as the fourth and fifth topic. The sixth topic is ***Weathering and transport of oil,*** including *Fate and transport,* and *Fugacity* as sub-topics. The seventh topic ***Response and recovery*** includes *Offshore response and recovery*, and *Shoreline response and recovery* two sub-topics. ***Evacuation and rescue*** is defined as the eighth topic, including sub-topics *Onboard evacuation and rescue* and *External evacuation and rescue*. ***Ecosystem impact*** is the ninth topic, including *Acute ecosystem impact*, *Chromic ecosystem impact* and *Emission impact*. The tenth, eleventh and twelfth topics are ***Health impact***, and ***Socio-cultural impact***, and ***Others*** respectively.

Based on this, the research topics in the shipping system for ice-covered waters are defined, in line with the main elements in Fig. 1 following the time and impact sequence. The topics are assigned with topic ID in Table 1, with sub-topics under each topic listed.

2.1.2. Research method

Research methods are quite diverse in general. Five categories are set up here to classify the methods applied in the research papers in CEARCTIC and CEPOLAR. The first group is 'Conceptual/Analytical method/Review', which mainly includes the qualitative methods, focusing on developing framework, conceptual model or review, etc. The second is 'Numerical modelling method', which includes numerical modellings, e.g. finite element method, own developed algorithms as well as system modelling, etc. The third category is 'Probabilistic modelling method', which largely relies on mature probabilititic theory

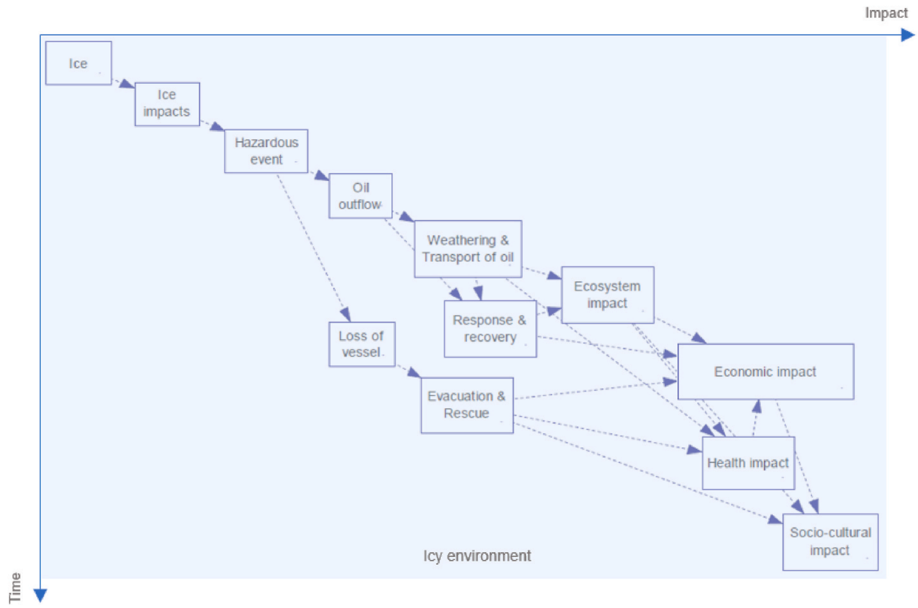

Fig. 1. Holistic framework for shipping system in ice-covered waters. The arrow indicates potential links following appearance and impact sequence.

Table 1
Research topic and sub-topic details for review and analysis.

Topic ID	Topic Name	Sub-topic ID and Name
1	Ice	1.1 Ice modelling
		1.2 Ice condition
2	Ice impact	2.1 Ice loading
		2.2 Ice resistance
		2.3 Transportation system in ice
3	Hazardous event	3.1 Ship besetting/delay
		3.2 Ship-ice collision
		3.3 Ship-ship collision/grounding
		3.4 Hull damage
4	Oil outflow	4 Oil outflow
5	Loss of vessel	5 Loss of vessel
6	Weathering and transport of oil	6.1 Fate and transport
		6.2 Fugacity
7	Response and recovery	7.1 Offshore response and recovery
		7.2 Shoreline response and recovery
8	Evacuation and rescue	8.1 Onboard evacuation and rescue
		8.2 External evacuation and rescue
9	Ecosystem impact	9.1 Acute ecosystem impact
		9.2 Chromic ecosystem impact
		9.3 Emission impact
10	Economic impact	10 Economic (reputation) impact
11	Health impact	11 Health impact
12	Socio-cultural impact	12 Socio-cultural impact
13	Others	13 Others

and modelling, including e.g. probability design method, Bayesian modelling, etc. The fourth is 'Statistical/Data analysis', which focuses more on data analysis with different approaches. The fifth is 'Experiment/Measurement method', mainly refers to experimental or full scale tests. The category of methods and their IDs are listed in Table 2.

Table 2
Method category and ID.

Method ID	Category name
1	Conceptual/Analytical method/Review
2	Numerical modelling method
3	Probabilistic modelling method
4	Statistical/Data analysis
5	Experiments/Measurements method

2.1.3. *Practical utilization purpose*

When the research topics and methods are reviewed and analyzed, the practical utilization purposes of the papers are also important to know so that how and where to use the knowledge developed in the papers can be considered and implemented in practical governance. This helps link the papers to practical applications in the risk governance process. Two basic groups of the practical utilization purposes are divided based the criteria on whether the paper aims to generate a practically useable model. Therefore, the first purpose category is defined as prediction purpose, where papers aim to generate models for specific prediction purpose. The second is defined as analysis purpose, i.e., non-prediction purpose, where papers aim to generate relevant knowledge foundations, insights, or discussions. In the cases that papers develop predictive models and further apply the models to generate relevant analysis and knowledge, they are classified in the prediction purpose category.

2.1.4. *Risk governance*

The review and analysis of risk goverance feature focuses on application relations of papers in the risk management framework as the final aim is to contribute to the risk management on theshipping system in ice-covered waters. There is a lack of analysis on papers from practical risk management perspective, i.e. where and how do the publications and models contribute in practical risk management. This analysis helps to form the toolbox for risk management in Section 2.2.

2.1.4.1. General risk goverance. The risk governance can be generally divided into two categories: operational risk management and strategic risk management. Operational risk management usually considers from real-time or short-term management perspective towards practical usage. While strategic risk management aims more from long-term perspective, e.g., managing the risk from design and planning phase. Based on this, four categories are set up to classify the papers according

Table 3
Practical utilization purpose category and ID.

Purpose ID	Category name
1	Prediction purpose: generate models for specific prediction
2	Analysis purpose: generate knowledge foundations, insight, discussions

to their potential general utilization group in the risk management framework, as listed in Table 4. Other means it does not have the risk management purpose.

2.1.4.2. Risk management stage. In addition to the general risk governance purpose, risk management is constituted by several stages. According to the ISO 31000:2018 International Standard on Risk Management, the process of risk management is composed of five stages, as shown in Fig. 2. The five main stages are: 1) establishing the context, 2) risk identification, 3) risk analysis, 4) risk evaluation, and 5) risk treatment. Steps 2) to 4), i.e., risk identification, analysis, and evaluation, are usually referred to as risk assessment, as also indicated by the gray block in Fig. 2. Risk treatment may also be called risk management, i.e. practical actions.

Stage 1 establishing the context usually targets to define the limit of the system to be assessed, i.e., in this stage, it usually involves defining scope, external and internal context, as well as risk criteria. Stage 2 risk identification aims to find, recognize and describe risks that might prevent a system to achieve its objectives. The purpose of stage 3 risk analysis is to comprehend the nature of risk and its characteristics, including its likelihood and consequences with underlying strength of evidence (Lu et al., 2022). It consists of four main elements: i) estimating the probability of the event occurrence, ii) estimating the severity of the consequences in case of event occurrence, iii) assessing the strength of the evidence (SoE) for the probability and consequence estimation, iv) combining probability, consequence, and strength of evidence (SoE) in a risk scale. This is a vital stage and include four elements, research or tools usually only focuses on achieving one or several of the elements in risk analysis. Stage 4 risk evaluation involves comparing the results of the risk analysis with the established risk criteria to determine where additional action is required. After stage 4, risk treatment is on focus when the risk level is deemed to be too high or unacceptable. Appropriate risk control and mitigation measures are implemented in practice (HELCOM, 2018).

Table 5 summarizes the risk management stages and assigns corresponding IDs, to classify the publications based on their potentials for application in the corresponding category. In addition to the five stages, ID 6 Other is added to represent those which do not fit into any stage or do not have risk management purposes.

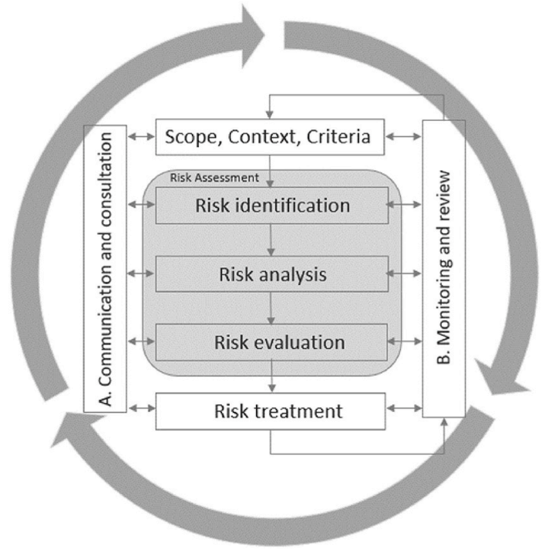

Fig. 2. The risk management process as described in ISO 31000:2018 (ISO, 2018).

Table 5
Risk management stage category and ID.

Risk management stage ID	Category name
1	Establishing the context
2	Risk identification
3	Risk analysis
4	Risk evaluation
5	Risk treatment
6	Other

2.2. Risk management applicability analysis

When the overall review and analysis are implemented, this paper steps into the second focus, i.e., forming applicable toolbox for practical risk management of shipping in ice-covered waters. This requires a further filtering of the publications and a further applicability analysis on the selected models. Based on the methods in Section 2.1, the relevant features for each publication are extracted and forms a matrix database. In order to find the 'practical models' which have potential to be applied practically in risk management process, a further selection procedure is established as shown in Fig. 3. The publications in CEARCTIC and CEPOLAR with classified features are the strating database. Three criteria are set in the selection process, i.e. 1) the paper needs to be a journal article which ensures that it is under more critical peer review process; 2) the paper has prediction purpose feature in term of practical utilization purpose (utilization purpose = 1) so that it has potential for estimating e.g. likelyhoods and/or consequences under varying practical conditions for risk management; 3) the paper is categorized in risk assessment stage 2 risk identification, stage 3 risk analysis and stage 4 risk evaluation. Once the publications are selected, a more detailed applicability analysis will be carried out in term of their subtopic, detailed methods, risk governance level, risk stage focus, risk management questions, knowledge and skill level needed, validation (SoE) level, and potential limitations, as indicated in process block in Fig. 3. In this way, a list of applicable models for risk management of shipping in ice-covered waters can be formed with detailed applicability analysis information, grouped in term of topics so that possible gaps for each topic and subtopic can also be seen.

Table 4
Risk goverance category and ID.

Risk goverance category ID	Category name
1	Operational risk management
2	Strategic risk management
3	Both
4	Other

Table 6 shows a detailed description of how a model is analyzed in the process stage, i.e., the detailed applicability analysis table. The first column division indicates that a model is assessed from five parts. The first is scope, which is reflected by the classified sub-topic. This helps to understand what problem the model contributes to, i.e., where the model is supposed to be used. The second is tool, which links to the detailed method the model applies, so that the user understands under what principle it works. The third is risk management focus, including risk governance level, risk stage focus and risk management question. Risk governance level refers to the classified operational and strategic risk management, and risk stage focus refers to the risk identification, risk analysis and risk evaluation stage focus. While risk management question refers to a further specific question the model aims to solve under the sub-topic scope. Applicability division regards to the practical applicability analysis of the model, including resource level and skill level needed, as well as validation level of the model. It also includes the overall applicability level, which is the combination of the previous three assessments. The principle of the combination follows criteria as shown in Table 7. The last division is comprehensiveness, which is mainly reflected by potential limitation of the model, i.e., the limitation

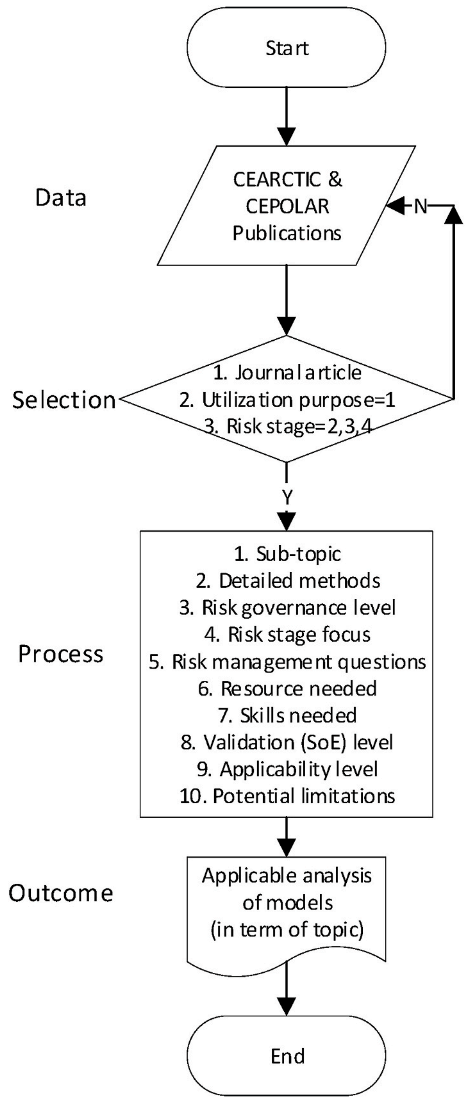

Fig. 3. Flowchart for applicability analysis.

of the model prediction under the risk management question, which often have many types of interdisciplinary elements.

2.3. Extensive review outside the project to supplement risk management toolbox

Review and analysis for the toolbox formed inside the project are conducted accordingly based on the framework and method described in Section 2.1 and 2.2. In order to have a wider understanding of the overall available models, additional review is carried out on papers outside the project. The review targets the publications in the same period as the project lasts, i.e., 2013–2022, for each sub-topic. The keywords and search criteria for relevant papers under each topic/sub-topic are as shown in Table 8. Only journal papers with quantitative prediction models are selected for the toolbox. The aim is to enrich the toolbox based on recent research and draw attention to potential gaps. Therefore, the models are not analyzed in detail as the ones inside the project, avoiding huge expansions.

3. Results and discussion

3.1. Review and analysis outcomes inside the project

3.1.1. Research topic

The journal and conference papers in CEARCTIC and CEPOLAR are reviewed and categorized according to the research topic framework in Fig. 1 and Table 1. The analysis and categorization are implemented based on the intention of which research topic the paper aims to contribute to. Fig. 4 shows the general distribution of the research papers on each topic. Topic ID 2 - ***Ice impact*** receives the highest attentions among all the publications. Topic ID 13 - other also has quite high research papers, it mainly relates to general method/concept development, relevant review, etc. or some specific modelling, e.g., machinery system, which do not fall into the current topic divisions. Topic ID 3 and 9, i.e., ***Hazardous event*** and ***Ecosystem impact*** have also relatively more publications. Topic ***Ice*** and ***Weathering and transport of oil*** rank next, and ***Response and recovery***, ***Evacuation and rescue***, ***Economic impact***, and ***Health impact*** rank lower. There are no publications focusing on topic ***Oil outflow***, ***Loss of vessel***, and ***Socio-cultural impact***. This could be attributed to the fact that oil spillage and loss of vessel may have relatively small difference comparing with open water, i.e., the research and models applicable in open water can also be utilized in ice conditions. Meanwhile, socio-cultural impact are more in the end stage of the holistic shipping system, therefore there are even less research foundation and experience or data to support such topics even though they are key elements in overall risks.

Fig. 5 shows a more subdivided distribution on each research sub-topic. Sub-topic ID 2.1 *Ice loading* has highest publications on its topic. Sub-topic ID 2.3 *Transportation system in ice* and Sub-topic ID 9.1 *Acute ecosystem impact* have slightly high number of papers on them. The other sub-topics have relatively well distributed research publications. It is also noticed that Sub-topic ID 2.2 *Ice resistance* has no relevant publication. The reason could be that it has relatively mature empirical and numerical models on this topic, and it is not the focus in the projects.

In addition, the analysis shows that Sub-topic ID 7.2 *Shoreline response and recovery* and Sub-topic ID 8.1 *Onboard evacuation and rescue* lack relevant research. In fact, shoreline response and recovery for oil spills in ice covered regions may be not needed immediately as ice may stop the oil to come ashore and the process of oil weathering is slowed down by the cold environment. However, it does not mean that it is not necessary at all. When in low ice concentration condition or ice-free period in the summer, oil will still endanger the shoreline like the open sea situations. Therefore, relevant research is still lacking. In addition, onboard evacuation and rescue research is quite relevant and needed as the external rescue and resources may be delayed and stopped due to the remoteness and harsh environment.

It should be noted that Sub-topic ID 3.4 *Hull damage* is in close relationship with Sub-topic ID 2.1 *Ice loading*, which sometimes makes

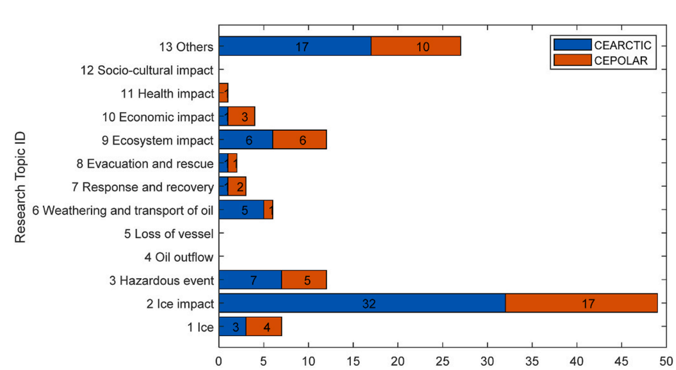

Fig. 4. Distribution of papers on each research topic, 1–13 are research topic IDs in Table 1.

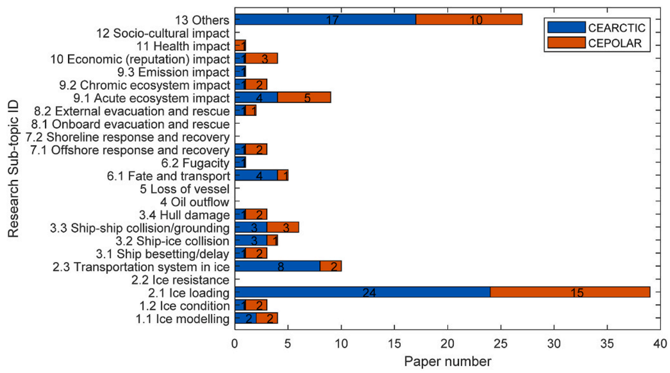

Fig. 5. Distribution of papers on each research sub-topic, 1.1–13 are sub-research topic IDs in Table 1.

the classification not so straightforward. For example, hull damage is highly relevant to ice loading in pure ice damage cases. In these cases, more focuses are given to the loading analysis, while the structural response is not in equal focus as the damage theory are likely quite similar with normal structural damage. This also applies to hull damage in ship-ship collision or grounding cases. However, it should be noted that the temperature is a quite different factor which may influences structural behavior. This may differ hull damage problems from open water cases. The temperature factor influence also applies to oil spillage topic (Topic ID 4), however not necessary to loss of vessel (Topic ID 5).

3.1.2. Research method

The distribution of research methods applied in the projects are demonstrated as in Fig. 6. The outer circle shows the result for CEARCTIC project, and the inner circle shows the results for CEPOLAR. Generally, Method ID 2 and 3 are the major methods applied. They represent numerical modelling method and probabilistic modelling method respectively. The probabilistic method remains at a stable percentage through the two projects periods, while the numerical modelling method shrinks around 12% during the second project stage. The reduced part of percentage is relocated to method ID 1 and 5 mainly, i.e., Experiments/Measurements method and Conceptual/Analytical method/Review.

3.1.3. Practical utilization purpose

The corresponding results for practical utilization purpose are shown in Fig. 7. It shows that papers in the second category, i.e., with analysis purpose, are the majority. The papers with prediction purpose are the ones which develop practical models. Although they are in a relatively small percentage comparing with non-prediction papers, the percentage increases from first project stage to the second one. This may also indicate the project is in a procedure towards a more practical application side. The practical utilization purpose is critical as it influences how the papers can be directly applied in risk management process.

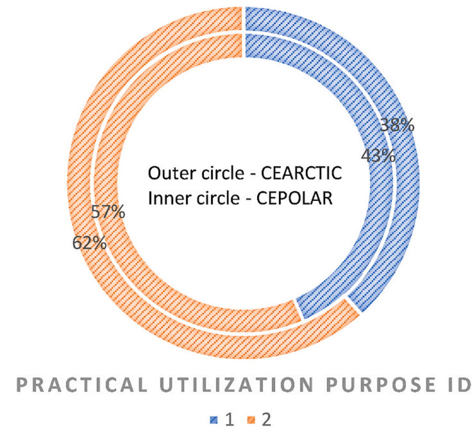

Fig. 7. Distribution of papers on each practical utilization purpose category. 1–2 are the practical utilization purpose IDs in Table 3.

3.1.4. Risk governace

3.1.4.1. General risk goverance. Fig. 8 shows the results for classifications of the papers in term of general risk governance. Generally, the risk goverance category ID 4 (Other) accounts for more or less half of the whole publications in both project stages, which means that this part of papers are not directly applicable for practical risk management. While the other half can contribute to facilitize or enrich the toolbox which can be used in the risk management for shipping system in ice-covered waters. Among them, papers towards usage in strategic risk management are the majority. Detailed distribution results on the risk management stages are illustrated in following section.

3.1.4.2. Risk management process. Fig. 9 demonstrates the classification results for risk management stages. More than half of the publications are in the category ID 6, which means they are not suitable for the application in the risk management process directly. This percentage is larger than the corresponding percentage for general risk governance ID

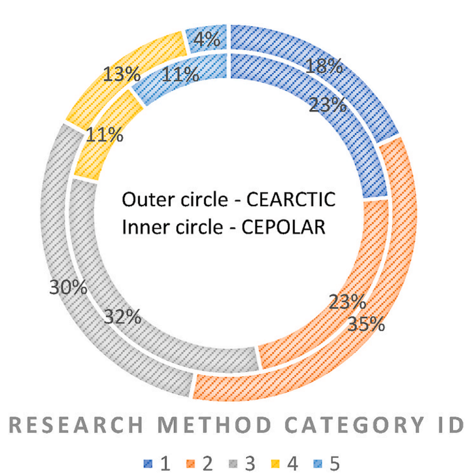

Fig. 6. Distribution of papers on each research method category, 1–5 are the research method IDs in Table 2.

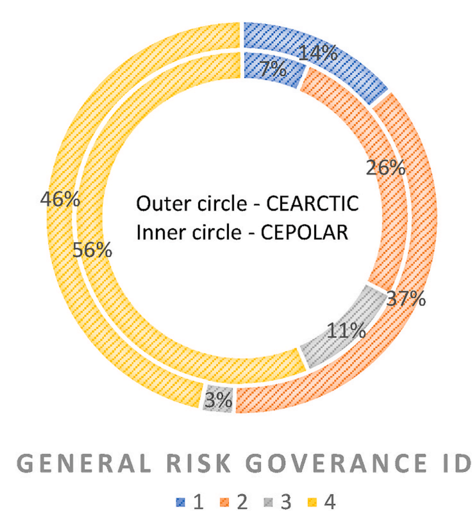

Fig. 8. Distribution of papers on general risk governance category, 1–4 are risk governance IDs in Table 4.

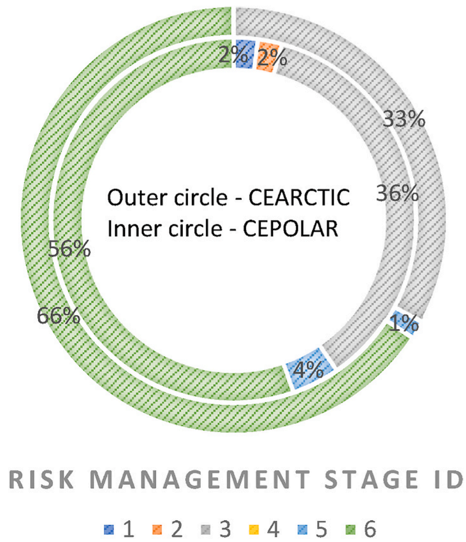

Fig. 9. Distribution of papers on each risk management stage category, 1–5 are risk management stage IDs in Table 5.

4, indicating that although some papers fit into the general risk governance ID 1–3, i.e., operational and strategic risk management, it is still difficult to group them to practical risk management stages. In the five risk management stages, ID 3 has the majority papers, i.e., the papers largely contribute to the potential toolbox in ID 3, i.e., risk analysis.

3.2. Risk management applicability analysis outcomes

Section 3.1 presents the review and analysis results regarding the designed features, which works as a foundation for forming applicable toolbox and their applicability analysis for risk management of shipping in ice-covered waters. With the obtained results in Section 3.1 and following the procedure in Fig. 3 in Section 2.2, a list of applicable models with relevant applicability analysis features defined in Table 6 are obtained. The list of applicable models is regarded as the applicable toolbox, and they are presented in term of topic so that it can be clearly seen what tools are available under specific topic and sub-topic. Tables 9–14 demonstrate the model details and relevant analysis for each topic respectively.

Table 9 shows the toolbox under ice impact topic, covering two sub-topics: ice loading and transportation system in ice - ice routing. Among the eight models, six are for ice loading prediction. The letter A and P in the model ID refers CEARCTIC (A) and CEPOLAR (P) projects. The questions the six models try to answer are either short-term or long-term peak ice loads on ship structures, which can be used in risk analysis stage for probability estimation of structure damage under the ice loads, expressed as risk analysis - P in Table 7. The models P2, P45 and P54 are on estimating long-term ice loads, therefore they can be applied in the strategic risk management, regarding the ship design. Models P1, A17, A32 are on short-term ice loads prediction, and they can be used for operational risk management during ship operation. Meanwhile, they are also suitable for strategic risk management for route planning for ships. Models P1, A17, A32 are all Bayesian hierarchical models, require medium level skill and relatively low or medium resources as indicated in Table 7. P2, P45 and P54 models are based on event-maximum method and probability distributions, also having low or medium level resource and skill requirements. The applicability levels for corresponding models are assessed based on Table 7 in Section 2.2. As the models are mainly built based on the measured ice load data, the potential limitations exist are the limitations of data, i.e., mainly on limited measurement locations, limited hull forms and operation modes.

Two models A67 and P36 are for the usage in transportation system in ice - ice routing. The model A67 applies finite element method to find the optimal route in ice. However it requires detailed costal and ice map, therefore resource level needed is relatively high. Considering it does not have relevant validation, the applicability level is rated as L-M accordingly. The model P36 extends POLARIS method so that it considers not only the potential hazardous ice conditions (P), but also the consequences (C) on environment, etc. The validation for this seems not possible, thus it is not considered and the applicability level is rated as M based on other two elements. There are also obvious limitations. One is that it requires certain information regarding its divided categories, which may be not easy to obtain for the polar regions. The other is that the factors proposed for calculating the index may still need more investigations and discussions although validation may be not achievable.

Table 10 shows the toolbox under hazardous events topic, covering sub-topics including besetting, ship-ice collision and ship-ship collision. Among the six models, two are related with beset subtopic, one is on ship-ship collision subtopic and the rest is for ship-ice or -iceberg collisions. The model P40 for ship besetting in ice aims to estimate the holistic besetting probabilities in different ice conditions using hierarchical Bayesian method, which is more suitable for strategic risk management.

Table 6
Applicability analysis division and process.

Division	Process	Description
Scope	Sub-topic	The sub-topics are defined in Table 1
Tool	Detailed method	The method is the main direct method applied
Risk management focus	Risk governance level	The risk governance level is based on Table 4
	Risk stage focus	The risk stage is based on stages in Table 5 with focus indicated, e.g., focus on likelihood (P) estimation or consequence (C), etc.
	Risk management question	The question is the specific problem the model aims to tackle with, under the sub-topic content
Applicability	Resource level needed	The resource is classified into three levels: low, medium, high based on how much other information/inputs is needed to activate the model
	Skill level needed	The skill is classified into three levels: low, medium, high based on how much skill is needed to apply the model
	Validation (SoE) level	The validation is classified into three levels: low, medium, high based on how much work is carried out to validate the model
	Applicability level	The applicability is classified into three levels: low, medium, high based on the combination of resource, skill, and validation level
Comprehensiveness	Potential limitation	The potential limitation is the limitation of the model prediction under the risk management question

Table 7
Applicability level assessment criteria. L-Low, M-Medium, H-High. '/' means 'or'.

Resource level needed	Skill level needed	Validation (SoE) level	Applicability level
H	H	L	L
L/M	H	L	L-M
L/M/H	M/L	L	L-M
L/M	L/M	M	M
H	L/M/H	M	M-L
L/M	H	M	M-L
L	L	H	H
L	M/H	H	H-M
M/H	L/M/H	H	H-M

Table 8
Keywords and search criteria for papers under each topic/sub-topic for additional review.

Topic ID	Topic Name	Sub-topic ID and Name	Key words (within year 2013–2022; journal papers; predictive models)
1	Ice	1.1 Ice modelling	TS=("ice constitutive model") OR TS=("ice material model")
		1.2 Ice condition	TS=("ice condition modelling") OR TS=("ice thickness model") OR TS=("ice concentration model") OR TS=("ice growth model")
2	Ice impact	2.1 Ice loading	TS=("ice loads") AND TS=("ship")
		2.2 Ice resistance	TS=("resistance") AND TS=("ship") AND TS=("ice") OR TS=("global ice loads")
		2.3 Transportation system in ice	(TS=("Arctic transportation") OR TS=("ice navigation") OR TS=("ice routing"))
3	Hazardous event	3.1 Ship besetting/delay	(TS=("besetting") AND TS=("ice") AND TS=("ship"))
		3.2 Ship-ice collision	(TS=("collision") AND TS=("ice") AND TS=("ship"))
		3.3 Ship-ship collision/grounding	(TS=("ship collision") AND TS=("ice")); (TS=("ship grounding") AND TS=("ice"))
		3.4 Hull damage	(TS=("hull damage") AND (TS=("ice") OR TS=("Arctic")))
4	Oil outflow	4 Oil outflow	((TS=("oil outflow") AND TS=("ship"))AND (TS=("ice") OR TS=("Arctic")))
5	Loss of vessel	5 Loss of vessel	(((TS=("foundering") OR TS=("sinking") OR TS=("flooding")) AND TS=("ship")) AND (TS=("ice") OR TS=("Arctic")))
6	Weathering and transport of oil	6.1 Fate and transport 6.2 Fugacity	(((TS=("weathering") OR TS=("transport")) AND TS=("oil")) AND (TS=("ice") OR TS=("Arctic")))
7	Response and recovery	7.1 Offshore response and recovery 7.2 Shoreline response and recovery	(((TS=("response") OR TS=("recovery")) AND TS=("oil spill")) AND (TS=("ice") OR TS=("Arctic")))
8	Evacuation and rescue	8.1 Onboard evacuation and rescue 8.2 External evacuation and rescue	(((TS=("evacuation") OR TS=("rescue")) AND TS=("ship")) AND (TS=("ice") OR TS=("Arctic")))
9	Ecosystem impact	9.1 Acute ecosystem impact 9.2 Chromic ecosystem impact	(((TS=("environmental") OR TS=("ecosystem")) AND TS=("accident")) AND (TS=("ice") OR TS=("Arctic")))
		9.3 Emission impact	((TS=("emission") AND TS=("shipping")) AND (TS=("ice") OR TS=("Arctic")))
10	Economic impact	10 Economic (reputation) impact	(((TS=("economic") OR TS=("socioeconomic") OR TS=("cost")) AND (TS=("accident") OR TS=("oil spill"))) AND (TS=("ice") OR TS=("Arctic")))
11	Health impact	11 Health impact	(((TS=("health impact") OR TS=("life")) AND (TS=("ship") OR TS=("oil spill"))) AND (TS=("ice") OR TS=("Arctic")))
12	Socio-cultural impact	12 Socio-cultural impact	(((TS=("socio-culture impact") OR TS=("cultural")) AND (TS=("accident") OR TS=("oil spill"))) AND (TS=("ice") OR TS=("Arctic")))

The model requires medium level resource and skill and has relatively high validation level. The potential limitation is that the data-based model uses the general level information and lacks inclusion of further detailed data on ship operating profile, other ice features, ship ice-going capability, etc. The model P53 aims to predict besetting ice conditions for both independent and escort operation using numerical modelling of ship transit in ice, which is suitable for both operational and strategic risk management. It is rated as H-M as applicability level as Model P40.

The other four models all utilize relevant Bayesian Network methods. The model P12 combines NaSch traffic model with Bayesian Networks to estimate ship-ship collision probability during convoy. It can be used for operational or strategic risk management depending on the available information level. The model requires medium level resource and skill, but is not validated, therefore rated into L-M category for its applicability level. Models P8 and A25 address the ship-ice collision probability for operational risk management. They require various type of environmental inputs for the model and have relatively medium and low validation level. As the models target the avoidance of ship-ice collision, therefore they are designed most likely for open water navigation in the polar area and has limited scope of operation. The model A14 focuses on the collision probability of ship and iceberg. The model has good utilization features with low resource and skill needed. However, it has no validation which leads to relatively L-M applicability level. The limitation of the model is that the (prior) probability feeding into the model may be not accurate due to various challenges and uncertainties according to the paper.

Table 11 shows the toolbox under weathering and transport of oil topic, covering sub-topics including fate and transport, and fugacity. The model A11 develops numerical modelling to estimate the spilled oil state for contingency planning focusing the consequence (C) side of risk management. It requires various spilled oil and other information, therefore considered having medium level requirement of resources. The skill level needed is rated as medium as other models since it is an algorithm-based model. The validation level is considered as medium as the model is compared and modified according to experimental data, which results M for applicability level. The model has integrated various good features; however, the potential limitation is that the model is slightly revised based on single experimental data, which may need further investigations. Meanwhile, the model does not couple with e.g., current movement, etc., which may give some limitation for practical utilization. The model A10 aims to estimate the concentration of oil in different media through numerical modelling. It has medium level resource and skill requirement, however, has no validation implemented. Therefore, the applicability level is rated as L-M. The limitation as pointed out in the paper is that the model may be not effective for evaluating the partition of high concentration chemicals and encapsulated oil, and current is not considered in the modelling.

Table 12 shows the toolbox under response and recovery topic for subtopic offshore response and recovery. The model P9 applies Bayesian Network method and aims to help decision making on selecting the response and recovery approaches for spilled oil in the operational risk management on the consequence (C) side. The model is considered to require high level resource as it requires more accurate data for better predictions. Considering the low skill level required and low validation level, the applicability is rated as L-M. The limitation is that the model needs reliable prior knowledge and data which are not yet there.

Table 13 shows the toolbox under ecosystem impact topic. The model P3 adopts index-based approach to assess the vulnerability of Arctic biota. The resource and skill level needed are considered as medium and low respectively. The uncertainty is discussed to some extent; therefore, it is considered as a medium level SoE, which gives a M applicability level. The potential limitation is that the model still uses a number of judgements and uniform distribution due to lack of relevant data. In addition, the model does not include the spatial features for both oil spill and Arctic biota, which limits the practical utilization. The model P13 aims to estimate the probability of marine fish cell damages

Table 9
Ice Impact toolbox and analysis.

Model ID	Subtopic	Method	Risk governance	Risk stage focus	Risk management question	Resource level needed	Skill level needed	Validation (SoE) level	Applicability level	Potential limitation
P1	Ice loading	Bayesian hierarchical models	Operational Stragetic	Risk analysis - P	What are the short-term peak ice loads for corresponding ice conditions	Low: ice thickness, ship speed	Medium: algorithm developed	High: posterior predictive checks	H-M	Limited local measurement data
P2	Ice loading	Event-maximum method	Stragetic	Risk analysis - P	What is the long-term maximum ice loads	Low: ice thickness, time	Low: developed p-h function/ curves	High: comparisons with similar curves	H	Limited ship hull and operation mode measurement data
P45	Ice loading	Extended event-maximum method	Stragetic	Risk analysis - P	What are the long term maximum ice loads	Medium: ice thickness, ice concentration, speed, time	Low: developed p-h-c function/ curves	High: six-year measurements	H-M	Limited ship hull and operation mode measurement data
P54	Ice loading	Probability distribution	Stragetic	Risk analysis - P	What are the short- and long term peak ice loads for corresponding ice conditions	Medium	Medium	High: goodness of fit	H-M	Limited ship hull and operation mode measurement data
A17	Ice loading	Bayesian hierarchical models	Operational Stragetic	Risk analysis - P	What are the short term peak ice loads for corresponding ice conditions	Low: ice thickness, ship speed	Medium: algorithm developed	High: cross validation	H-M	Limited ship hull, sea area and operation mode measurement data
A32	Ice loading	Bayesian hierarchical models	Operational Stragetic	Risk analysis - P	What are the short term peak ice loads for corresponding ice conditions	Medium: ice thickness, ship speed, latitude, air temperature, season time	Medium: algorithm developed	High: cross validation	H-M	Limited ship hull, sea area and operation mode measurement data
A67	Transportion system in ice: ice routing	Finite element method	Stragetic	Risk analysis	What is the optimal route	High: detail costal map, ice map	Medium: algorithm developed	Low: no validation or SoE	L-M	Require reliable detailed ice map, other constrains for shipping
P36	Transportion system in ice: ice routing	Extended POLARIS	Operational Stragetic	Risk analysis - P,C	What is the low-risk route considering all aspects	Medium	Low	–	M	Lack of relevant detailed information in relevant categories, need more investigation on the factor values

A – CEARCTIC, P – CEPOLAR.
P1 - Rotating ice cusps on ship's bow shoulder: Full-scale study on the cusp sizes and corresponding peak loads in different ice and operational conditions (Kotilainen et al., 2019).
P2 - Local pressures for ships in ice: Probabilistic analysis of full-scale line-load data (Shamaei et al., 2020).
P45 - A probabilistic method for long-term estimation of ice loads on ship hull (Li et al., 2021b).
P54 - Short-term statistics of ice loads on ship bow frames in floe ice fields: Full-scale measurements in the Antarctic ocean (Li et al., 2021a).
A17 - Predicting ice-induced load amplitudes on ship bow conditional on ice thickness and ship speed in the Baltic Sea (Kotilainen et al., 2017).
A32 - Predicting local ice loads on ship bow as a function of ice and operational conditions in the Southern Sea (Kotilainen et al., 2018).
A67 - A Finite Element Method-Based Potential Theory Approach for Optimal Ice Routing (Piehl et al., 2017).
P36 - A Framework for Integrating Life-Safety and Environmental Consequences into Conventional Arctic Shipping Risk Models (Browne et al., 2020).

to oil spill. The required resource and skill level are low, and the model considers validation through a general comparison. Therefore, validation level is considered as Medium, and the final applicability level is rated as M as well. The limitation of the model is that the CPT states are limited and the modelling of structure and CPTs lack SoE supports.

The model P16 uses Bayesian Networks approach to estimate the total mortality level of polar cod to oil spill. Likewise, the resource level and skill level needed are considered as low, while the validation level is considered as a level up to H as it includes two comparisons and certain level SoE analysis. Therefore, the applicability level is rated as H. However, it should also be noted that there is limited evidence on model structure construction and certain supporting data also have limitations as pointed out in the paper.

The model P35 also uses Bayesian Networks method to estimate oil

Table 10
Hazardous events toolbox and analysis.

Model ID	Subtopic	Method	Risk governance	Risk stage focus	Risk management question	Resource level needed	Skill level needed	Validation (SoE) level	Applicability level	Potential limitation
P40	Besetting	Hierarchical Bayesian model	Stragetic	Risk analysis - P	What are the probabilities for ships besetting in different ice conditions	Medium: ship category, ice concentration, sea area, travel distance	Medium: algorithm developed	High: posterior predictive uncertainty	H-M	It is a general level estimation with limitations on ship operating profile, ship ice-going capability, other ice features and environmental factors
P53	Besetting/ stuck	Numerical modelling	Operational Stragetic	Risk analysis - P	What are the risky situations for independent and escorted ships getting stuck in ice	Medium: ship information, operational input, ice information	Medium: algorithm developed	High: validation with AIS data	H-M	Limited ice breaking mechanism, ice drift is hard for estimation, ice towards ship side
P8	Ship-ice collision	Dynamic Bayesian Network	Operational	Risk analysis - P	What is the probability of ship ice collision	Medium: hourly environmental information	Medium: model developed	Medium: general uncertainty estimation	M	Limited for open water navigation in Arctic, need reliable prior knowledge
P12	Ship-ship collision	NaSch model with Bayesian Network	Operational Stragetic	Risk analysis - P	What is the probability of ship-ship collision during convoy	Medium: need simulation of traffic information	Medium: NaSch model + BN model developed	Low: no validation or SoE	L-M	Limitation for ice related effects on convoy
A14	Ship-iceberg collision	Bayesian Networks	Operational	Risk analysis - P	What is the probability of ship-iceberg collision what are the critical factors	Low	Low: developed model	Low: no validation or SoE	L-M	Probabilities obtained may not be accurate
A25	Ship-ice collision	Object-Oriented Bayesian Networks	Operational	Risk analysis - P	What is the probability for ship-ice collision	Medium: various types of initial information	Low: developed model	Low: no validation or SoE	L-M	Limited for open water navigation in Arctic, need reliable prior knowledge

P40 - Probability of a ship becoming beset in ice along the Northern Sea Route – A Bayesian analysis of real-life data (Vanhatalo et al., 2021).
P53 - A method for assessing ship operability in dynamic ice for independent navigation and escort operations (Lu et al., 2021).
P8 - A Dynamic Bayesian Network model for ship-ice collision risk in the Arctic waters (Khan et al., 2020).
P12 - A cellular automation model for convoy traffic in Arctic waters (Khan et al., 2019).
A14 - Arctic shipping accident scenario analysis using Bayesian Network approach (Afenyo et al., 2017b).
A25 - An operational risk analysis tool to analyze marine transportation in Arctic waters (Khan et al., 2018).

Table 11
Weathering and transport of oil toolbox and analysis.

Model ID	Subtopic	Method	Risk governance	Risk stage focus	Risk management question	Resource level needed	Skill level needed	Validation (SoE) level	Applicability level	Potential limitation
A11	Fate and transport	Numerical modelling	Operational Stragetic	Risk analysis - C	What is weathering and transport state of the spilled oil for contingency planning	Medium: Spilled oil information and wind, etc.	Medium: algorithm developed	Medium: compared and modified according to experiment data	M	Model is modified according to only one experiment, more data needed, limitation without coupling with current movement
A10	Fugacity	Numerical modelling	Operational	Risk analysis - C	What is the concentration of oil in different media	Medium	Medium: algorithm developed	Low: no validation or SoE	L-M	Not effective for evaluating the partition of high concentration chemicals, encapsulated oil not considered, no current

A11 - Modeling oil weathering and transport in sea ice (Afenyo et al., 2016).
A10 - Dynamic fugacity model for accidental oil release during Arctic shipping (Afenyo et al., 2016a).

Table 12
Response and recovery toolbox and analysis.

Model ID	Subtopic	Method	Risk governance	Risk stage focus	Risk management question	Resource level needed	Skill level needed	Validation (SoE) level	Applicability level	Potential limitation
P9	Offshore response and recovery	Object-Oriented Bayesian Networks	Operational	Risk analysis - C	What is cost-effectiveness response and recovery method for spilled oil	High: more accurate data needed for the model	Low: developed model	Low: no validation or SoE	L-M	It lacks reliable prior knowledge, data

P9 - An explorative object-oriented Bayesian network model for oil spill response in the Arctic Ocean (Afenyo et al., 2020).

Table 13
Ecosystem impact toolbox and analysis.

Model ID	Subtopic	Method	Risk governance	Risk stage focus	Risk management question	Resource level needed	Skill level needed	Validation (SoE) level	Applicability level	Potential limitation
P3	Acute ecosystem impact	Index-based approach	Stragetic	Risk analysis - C	Which Arctic biota is more vulnerable to oil spill	Medium	Low	Medium: inclusion of uncertainty source for SoE	M	Lack of data and a number of judgements and uniform distribution assigned, spatial features not included
P13	Acute ecosystem impact	Bayesian networks	Stragetic	Risk analysis - C	What is the probability of marine fish cell damages to oil spill	Low	Low	Medium: a general comparison	M	The states in the BNs are limited, the model structure and CPTs lack relevant SoE
P16	Acute ecosystem impact	Bayesian networks	Stragetic	Risk analysis - C	What is mortality level of polar cod to oil spill	Low	Low	High: two comparisons and certain level SoE	H	Limited evidence on model structure and supporting data may have limitations
P35	Acute ecosystem impact	Bayesian networks	Stragetic	Risk analysis - C	What are oil spill impacts to apex marine species and its cascading effects on the food web	Medium	Low	Low: no validation or SoE	L-M	The model structure and CPTs lack relevant SoE, assumptions are made
P39	Acute ecosystem impact	Probabilistic modelling	Stragetic	Risk analysis - C	What is the expected proportion of population to die after an accident on a shipping route	Medium	Medium	–	H-M	The model excludes the transport of oil by currents, ice, etc. and does not consider oil weathering
A4	Acute ecosystem impact	Probabilistic modelling	Stragetic	Risk analysis - P, C	What is the spatial risk of potential accidents posing to threatened species and habitat in GoF	Medium	High: spatial mapping	Low: no validation or SoE	L-M	Wintertime ice condition is exculded in the model; data used has limitations
A15	Acute ecosystem impact	Probabilistic modelling	Operational	Risk analysis - C	What is risk quotient index level for Arctic marine ecosystem based on oil exposure concentration after an oil spill	High	Medium: developed algorithm	Medium: uncertainty considered	M-L	Limited ice condition for despersion model; current not considered in modelling, lack of data in modelling

P3 - Index-based approach for estimating vulnerability of Arctic biota to oil spills (Nevalainen et al., 2019).
P13 - Arctic marine fish 'biotransformation toxicity' model for ecological risk assessment (Fahd et al., 2019).
P16 - Risk assessment of Arctic aquatic species using ecotoxicological biomarkers and Bayesian network (Fahd et al., 2020).
P35 - A food chain-based ecological risk assessment model for oil spills in the Arctic environment (Fahd et al., 2021).
P39 - Impacts of Oil Spills on Arctic Marine Ecosystems: A Quantitative and Probabilistic Risk Assessment Perspective (Helle et al., 2020).
A4 - Species and habitats in danger: estimating the relative risk posed by oil spills in the northern Baltic Sea (Helle et al., 2016)
A15 - A probabilistic ecological risk model for Arctic marine oil spills (Afenyo et al., 2017a).

spill impacts to apex marine species and its cascading effects on the food web. The validation level however is relatively low as no validation and obvious SoE analysis are implemented, which leads to L-M applicability level for the model. The limitation also exists in the lack of SoE support in model construction.

The model P39 applies probabilistic modelling approach to quantitively predict the expected proportion of population (polar bear, ringed seals, and walrus) to die after an accident on a shipping route. It is considered to have a medium level resource and skill requirement. The validation is considered not applicable for the model and the final applicability level is rated as H-M considering the overall good features of the model. The potential limitation is that the model does not include the weathering and transport of oil with ice and thus likely to underestimate the oiled area.

The model A4 utilizes probabilistic modelling approach to estimate the spatial risk of potential accidents and oil spill to threated species and habitat in the Gulf of Finland (GoF). It includes both probability modelling for oil spill using Bayesian Networks and consequence modelling using oil spreading probabilistic mapping with habitat and species data. The resource required is considered as medium and skill level needed is considered as high. As there is no obvious validation and SoE analysis, low is assigned to the validation level and the overall applicability level is rated as L-M. The obvious limitation is that wintertime ice condition is not in the scope of the model.

The model A15 aims to estimate a proposed risk quotient index level based on expose concentration modelling results after an oil spill to indicate the ecotoxicological risk level for Arctic marine ecosystem. It is considered to require relatively high resource to run the simulation and medium level skill. Validation level is considered as medium as uncertainty approach is included although no direction validation involved. The applicability level is therefore rated as M-L and the main limitations are the limited ice condition for dispersion model, current model not involved in modelling and lack of data.

Table 14 shows the toolbox under economic impact topic. The model P14 applies Bayesian Network modelling to estimate the habitat restoration costs for oil spill. The model has complex factors considered in the modelling. However, the limitation is that the states are relatively simple which restricts estimated outcomes. The resource level and skill level needed are considered as medium, so as the validation level where uncertainty is mentioned and considered to some extent. Therefore, the applicability level is rated as M accordingly. In general, the construction of the modelling lacks SoE analysis especially on CPTs, and cost values referred to may not be representative enough for Arctic regions. P55 model receives similar rates for its features. It establishes a good approach to obtain a total consequence cost of an accident. The potential limitation is that the underlying consequence cost estimations are based on simplified equations, which may need further investigations to have a more Arctic and ice condition oriented cost model.

3.3. Extensive review outcomes outside the project to supplement risk management toolbox

Section 3.2 forms a toolbox from the project with the applicability analysis. This section focuses on the enrichment of the toolbox from the models outside the project for each topic/sub-topic so that it can indicate where the tools may be lacking.

Under *Ice* topic, the project has no direct toolbox development under subtopic *Ice modelling* and *Ice condition*. The extensive review outside the project shows some model developments on both ice and ice condition modelling. There are several ice constitutive models and they are shown as below in Table 15. However, the general limitation is that ice as a material is affected by many factors, including temperature, brine and porosity, loading rate, etc. Many models only include a part of the characteristics for certain scenarios. In addition, all models describe the phenomenological relation between stress, strain, time, etc. The models of micromechanics such as grain boundary and dislocations, etc. seem lacking. Generally, there is no widely accepted ice model formed yet, which brings challenges to accurate modelling for a bigger scope.

For ice condition modelling (see Table 15), there are several new model features, e.g., using RADARSAT-2 image into numerical calculations to improve ice thickness estimation (Zhang et al., 2019), and enhanced Sea Ice Model for Arctic ice thickness (Appel, 2016), ice thickness estimation based on satellite-derived ice age (Liu et al., 2020), as well as brash ice growth model development (Riska et al., 2019). The models have improved some features comparing to the current available ice charts from different countries, however, still have various uncertainties and limitations on ice ridge and pressured ice information as mentioned by Bergström et al. (2022). In addition, the main challenge is that there is a number of oceanographic scale models based e.g. on satellite observation having typically the scale of few kilometers, but for ship performance and ice load modeling, models with scale of 10–100 m are needed, which do not exist.

Under *Ice impact* topic, the project itself has relatively good coverage for *Ice loading* sub-topic. However, it should be noted that the overall approach for ice loading estimation is data-driven based on ice loads measurement. The full scale and long-term measurement are scare thus very valuable, but limitations on the data as mentioned in Table 9 and in Section 3.2 are unavoidable. Therefore, the first-principle engineering modelling approach is suggested. The data and data-driven model can

Table 15
Ice toolbox supplement.

Topic	Subtopic	Models
Ice	Ice model	Yu et al. (2020); Xu et al. (2019); Cai et al. (2020); Song et al. (2019); Kim et al. (2015); Tippmann et al. (2013); Shi et al. (2017); Gao et al. (2015); Xu et al. (2019b)
	Ice conditions	Zhang et al. (2019); Appel (2016); Liu et al. (2020); Riska et al. (2019)

Table 14
Economic impact toolbox and analysis.

Model ID	Subtopic	Method	Risk governance	Risk stage focus	Risk management question	Resource level needed	Skill level needed	Validation (SoE) level	Applicability level	Potential limitation
P14	Economic impact	Object-oriented Bayesian network	Stragetic	Risk analysis - C	How large is the economic impact of habitat injury to oil spill	Medium	Medium	Medium: uncertainty considered	M	Cost values are not for Arctic regions; complex model but simple states and no SoE for BN
P55	Economic impact	–	Operational Stragetic	Risk analysis - C	How to quantify total consequence cost	Medium	Medium	Medium: comparison made	M	Underlying cost estimation is simplified

P14 - Dynamic ecological risk modelling of hydrocarbon release scenarios in Arctic waters (Sajid et al., 2020).
P55 - A general method to combine environmental and life-safety consequences of Arctic ship accidents (Browne et al., 2022).

Table 16
Ice Impact toolbox supplement.

Topic	Subtopic	Models
Ice impact	Ice loading	Wang et al., 2018, 2019; Chai et al. (2018); Erceg et al. (2022); Wang et al. (2018)
	Ice resistance	Tan et al. (2014); Xuan et al. (2021); Li et al. (2020); Li et al. (2020b); Ni et al. (2020); Liu and Ji (2021); Zong and Zhou (2019); Huang et al. (2021); Sazonov and Dobrodeev (2021); Li et al., 2021; Zhang et al. (2022); Luo et al. (2020); Xie et al. (2022); Gong et al. (2019); Huang et al. (2020); Huang et al. (2021b); Yang et al. (2021); Kim et al. (2020); Sun et al. (2022); Milaković et al. (2020)
	Ice routing	Ari et al. (2013); Choi et al. (2015); Liu et al. (2016); Lehtola et al. (2019); Zvyagina and Zvyagin (2022); Topaj et al. (2019)

give good supports to the validation for the engineering approach. This approach however requires more accurate ice behaviour modelling in the *Ice* topic so that some ice loading phenomena e.g., ice crushing can be better modelled. The predictive models outside the project focusing on local loads are relatively limited (see Table 16). Chai et al. (2018) applied probabilistic method and Erceg et al. (2022) used semi-empirical numerical method to simulate the local ice loads, which adds some different feature to the toolbox. Two models (Wang et al., 2018 and Wang et al., 2019) using peridynamic method and cohesive element method researched the loads on propellers, which enriches the toolbox on this topic as the predictive models for loads on propellers are not studied in the project. In general, limited models can be found on loads on propellers, thus it requires more investigations.

Ice resistance sub-topic inside the project is blank as mentioned early, this is purely because it is not the focus in the project. Outside the project, quite extensive ice resistance models or global ice loads models can be found (see Table 16), applying various methods including semi-empirical numerical method, discrete element method (DEM), peridynamic method (PD), finite element method (FEM), computational fluid dynamics (CFD)-DEM method, etc. The models can be categorized based on their scenario features into e.g. models on global ice loas in level ice (Tan et al., 2014; Xuan et al., 2021; Li et al., 2020; Li et al., 2020b; Ni et al., 2020) as well as escort in level ice (Liu and Ji, 2021), ice resistance in pack and thin ice (Zong and Zhou, 2019), ship resistance in open-water ice channel (Huang et al., 2021), narrow ice channel (Sazonov and Dobrodeev, 2021; Li et al., 2021) as well as in restricted brash ice channel (Zhang et al., 2022; Luo et al., 2020; Xie et al., 2022), ship resistance in unconsolidated ridges (Gong et al., 2019), resistance in ice floes (Huang et al., 2020, 2021b), broken ice pieces (Yang et al., 2021). In addition, Kim et al. (2020) and Sun et al. (2022) applied machine learning method to estimate ice resistance based on model test data, while Milaković et al. (2020) established machine learning model based on simulation data. Generally, a wide range of models are developed on ice resistance topic. While numerical models rely much on the applied ice material models, the lack of widely accepted ice model poses an obvious limitation. Meanwhile, lack of full-scale data of different ships limits the validations. Additionally, ship–wave–ice interaction is not often seen and need further attentions.

Transportation system in ice sub-topic originally aims for the themes related to the system level analysis having bigger scope than only local structure or individual ship level scope, e.g., routing of ships through ice cover and transportation system design. Several models outside the project are found. Most of them applied cell-based approach (A* and Dijkstra's algorithm), e.g., Ari et al. (2013), Choi et al. (2015), Liu et al. (2016), and Lehtola et al. (2019). Zvyagina and Zvyagin (2022) considered multi-objective problem of ice navigation routing, and Topaj et al. (2019) applied both cell-based and wave-based ice routing approaches with icebreaker assistance considered. Although various optimization methods are applied, one of the core parts, i.e., the ship performance models utilized for the optimization is usually simplified, which may underestimate some time-consuming events, e.g., besetting in pressured ice. In addition, ice routing models considering ice resistance are common, but few considers meanwhile the ice loading on ship structures, especially for those unreinforced conventional ships. Furthermore, the more comprehensive routing model may require not only ship-related ice resistance and loading, but also risk-based environmental and human aspects like model P36 (Browne et al., 2020) using extended POLARIS. However, this requires extensive information on a number of parameters.

Under *Hazardous event* topic, *Ship besetting* sub-topic in the project has two models, applying data-driven and engineering modelling approaches. Outside the project, several models are found, including Xu et al. (2022), Turnbull et al. (2019), Fu et al. (2016) and Fu et al. (2018) (see Table 17). They are all probabilistic oriented model, which have a common feature that ship-related parameters are limitedly considered. In addition, although independent and escort operations are included in the engineering modelling approaches, convoy operation, i.e., multi-vessel following the leading icebreaker situation may need some specific consideration.

Ship-ice collision sub-topic in the project has three models while only one method, aiming on the probability side for ship-ice and iceberg collision. Outside the project, two models which consider the contact between ship and a big ice floe or iceberg are found. Cai et al. (2022) presented an approximate analytical plastic damage prediction method for ship plate. Obisesan and Sriramula (2018) proposed an approach considering both collision probability with iceberg and consequence. Ship-iceberg collision still has large uncertainty to model e.g., on the iceberg appearance and possible collision with the ship.

Ship-ship collision/grounding sub-topic has only one model in the project, and it only concerns the ship-ship collision probability prediction in convoy situation based on simulated traffic features. Outside the project, some probabilistic models are available. Baksh et al. (2018) established a BN model for collision and grounding, and Fu et al. (2022) built up a BN model for grounding in Arctic. However, the relevant ice and operation features in ice seem not thoroughly considered. The collisions for different encounter situations as well as passive ship groundings in certain ice conditions need further investigations. In addition, ship-ship collision in convoy mode is to some extent predictable and avoidable by modelling different situations, e.g., modelling the safe distance between ships and ship break out from the channel capabilities. The model P53 (Lu et al., 2021) under ship besetting topic has considered the ship-ship collision during escort as a boundary but did not further investigate it. Relevant engineering-based models are therefore needed. Park et al. (2015a; 2015b) studied the crashworthiness of ships in the Arctic considering the low temperature conditions. This can also be considered in the *Hull damage* sub-topic as it relates to the damage mechanics in the Arctic low temperature conditions. Many research did not specifically consider damage mechanism in ice conditions, regarding it similar as open water conventional conditions. However, the difference low temperature potentially brings to the structure should be modelled. In addition, further fatigue induced

Table 17
Hazardous event toolbox supplement.

Topic	Subtopic	Models
Hazardous event	Besetting	Xu et al. (2022); Turnbull et al. (2019); Fu et al. (2016); Fu et al. (2018)
	Ship-ice collision	Cai et al. (2022); Obisesan and Sriramula (2018)
	Ship-ship collision/ grounding	Baksh et al. (2018); Fu et al. (2022); Park et al. (2015a)
	Hull damage	Park et al. (2015a; 2015b)

damage may need more investigations.

Under *Oil outflow and Loss of vessel* topics, there are no formed toolbox. This may be because the principles are likely same as open water conventional situations where oil outflow and flooding models are developed. However, whether ice existence influences the process or what kind of damage situations ice may play a role are not clear yet, which deserves modified models.

Under *Weathering and transport of oil* topic, outside the project, several models exist for *Fate and transport* sub-topic (see Table 18). French-McCay et al. (2017), Blanken et al. (2017), Nordam et al. (2019), Babaei and Watson (2020) and Arneborg et al. (2017) improved oil spill trajectory modelling in ice conditions; Nordam et al. (2020) focused on oil thickness modelling in ice edge. Yang et al. (2015) developed fugacity-based approach for multimedia fate modelling of oil spill in ice under *Fugacity* sub-topic. In addition to the models, the oil encapsulation in ice is needed. As considering its movement with current, it may pose oil release risk in other sea or shore regions when ice is melted during summertime.

Under *Response and recovery* topic, there are several reviews regarding *Offshore response and recovery* sub-topic outside the project (see Table 19). Yang et al. (2021) and Li et al. (2016) reviewed decision support tools and practices for oil spill responses in general, only shortly mentioned Arctic conditions. Wilkinson et al. (2017) and Bullock et al. (2019) reviewed oil spill response capabilities and technologies for ice-covered Arctic waters and in-situ burning with chemical herders respectively. Wenning et al. (2018) summarized Current practices and compared six different risk assessment methods of oil spill in the Arctic, including quantitative and qualitative approaches. However, although there are extensive illustrations and approaches, the models focusing on calculating the recovery effectiveness, i.e., how much oil can be recovered or burning and dispersant effectiveness for an oil spill are rare. Lu et al. (2019) developed a model for estimating the recovery effectiveness for oil spills in ice, however only for mechanical recovery approach. Therefore, such goal based response and recovery models are further needed for relevant decision making.

Shoreline response and recovery sub-topic has no model founded. Some further investigations are needed in case oil are temporarily stopped by ice or encapsulated inside ice and comes to shore when it is released.

Under *Evacuation and rescue* topic, there are few models addressing evacuation and rescue quantitively outside the project (see Table 20). Browne et al. (2021) inside the project completed some scenario based analysis using expert knowledge for understanding the consequence. Kruke and Auestad (2021) studied emergency preparedness and rescue in Arctic waters through previous ship incidents and accidents and SARex exercises. Shan and Zhang (2019) researched the allocation of rescue bases in the Arctic. Therefore, both *Onboard and External evacuation and rescue* require modelling and simulations to enhance sufficient planning and preparedness.

Under *Ecosystem impact* topic, *Acute ecosystem impact* sub-topic has seven models applying more than three methods in the project, covering relatively various aspects well. More relevant data about marine life or experimental data could be planned for further modelling improvement as it is vital but rare for polar regions. Outside the project, quantitative models for *Acute and Chromic ecosystem impact* sub-topics are not founded. While models for *Emission impact* sub-topics received wide attentions (see Table 21). Browse et al. (2013) quantified the contribution of future Arctic shipping to high-latitude black carbon deposition; Schröder et al. (2017) investigated the exhaust emissions of ships navigating in arctic waters; Jing et al. (2021) developed a system dynamics model for Arctic shipping CO2 emission projection; Gong et al. (2018) used Environment and Climate Change Canada's on-line air quality forecast model to investigate the contribution from the marine shipping emissions over the Canadian Arctic waters; Winther et al. (2014) presented geospatial ship type specific emission results; Chen et al. (2021) focused on passenger ship pollutants in the Arctic; Chen et al. (2022) calculated the emissions inventory for vessels operating in the Arctic region; Zhang et al. (2019) quantitively reviewed potential technical and operational solutions to reduce BC emission from shipping.

Under *Economic impact* topic, one model (Afenyo et al., 2022) outside the project tried to develop the socioeconomic impacts of oil spill from Arctic shipping, considering natural damage, economic loss, response cost, etc. (see Table 22). However, like in the other models in the project, the real economic related values for oil spill, including clean-up cost, natural resource damage and socioeconomic loss for ice-covered waters are not sufficient currently. They need more investigations and modelling to be able to support the better overall economic impact estimation.

Under *Health impact* topic, outside the project, Geels et al. (2021) studied shipping emissions and related impact on air pollution and human health. No oil spill impact models on human health are seen. Although in the project Browne et al. (2021) studied evacuation related life-safety consequence based on expert knowledge, there still lack health and life impact models for rescue and evacuation situations. *Socio-cultural impact* topic has no model yet and in long term this requires further studies.

Until here, the toolbox for each topic/sub-topic have been

Table 18
Weathering and transport of oil toolbox supplement.

Topic	Subtopic	Models
Weathering and transport of oil	Fate and transport	French-McCay et al. (2017); Blanken et al. (2017); Nordam et al. (2019); Babaei and Watson (2020); Arneborg et al. (2017); Nordam et al. (2020)
	Fugacity	Yang et al. (2015)

Table 19
Response and recovery toolbox supplement.

Topic	Subtopic	Models
Response and recovery	Offshore response and recovery	Wilkinson et al. (2017); Bullock et al. (2019); Wenning et al. (2018); Lu et al. (2019)
	Shoreline response and recovery	–

Table 20
Evacuation and rescue toolbox supplement.

Topic	Subtopic	Models
Evacuation and rescue	Onboard evacuation and rescue	–
	External evacuation and rescue	Shan and Zhang (2019)

Table 21
Ecosystem impact toolbox supplement.

Topic	Subtopic	Models
Ecosystem impact	Acute ecosystem impact	–
	Chromic ecosystem impact	–
	Emission impact	Browse et al. (2013); Schröder et al. (2017); Jing et al. (2021); Gong et al. (2018); Winther et al. (2014); Chen et al. (2021); Chen et al. (2022)

Table 22
Economic and health impact toolbox supplement.

Topic	Subtopic	Models
Economic impact	Economic impact	Afenyo et al. (2022)
Health impact	Health impact	Geels et al. (2021)

completed, covering year 2013–2022. The models inside the project are analyzed in a more detailed and structured way in terms of applicability. The models outside the project are presented in a general way without detailed applicability analysis. Forming an applicability analysis for each model may be supportive for practical usage, however since the procedure of the applicability analysis is established and demonstrated for the models inside the project, the rest is left for future work to avoid huge expansions in this paper.

It should be noted that this paper may also underestimate the overall research work for each topic/sub-topic as it only focuses on so called quantitative models. Qualitative information and models are also usually useful for decision making. In addition, criteria to determine a quantitative model are subjective, which may slightly differ from individuals. However, importantly this paper establishes framework, structures, and procedures, so people can have different assessment based on their intensions to shape the toolbox for their purposes.

Additionally, this paper established framework considering typical hazards for ships focusing on ice-covered waters. Some specific accidents e.g., fire, LNG vessel accidents and leakages are notincluded in the framework.

4. Conclusion

This paper creates a holistic framework for risk management of shipping in ice-covered waters. Based on the framework, it carries out a deep review and analysis for a comprehensive and long-term project specifically focusing on holistic safe polar shipping. The review and analysis further form a practical toolbox which can be utilized for operational and strategic risk management. A structured applicability analysis procedure is established, and example analysis are made for the toolbox within the project. An extensive review is conducted outside the project for the same period 2013–2022 to supplement the formed toolbox inside the project, constituting a more comprehensive toolbox. The overall toolbox helps indicate the gaps and limitations of the current research and approaches, with future directions are discussed and identified. Such specific toolboxes are formed for the first time for shipping system risk management in ice-covered waters, providing a foundation for extending and growing the practical managing boxes for different scenarios. It should be noted that some rating is used for applicability analysis, it only aims to indicate the applicability features and does not represent research quality as the research question and potential boundary limitations of each research are not comparable.

To further develop and enhance the toolbox to alive, it is suggested to further screen relevant research and models and use the established framework to classify potential models into the toolbox under corresponding topics. In some conditions, not only the ice-oriented research should be considered, but also some research for open water situations can be merged if suitable.

Overall, the review inside and outside the project clearly shows how wide and multidisciplinary the scope for risk management of shipping in ice covered waters is, especially on the hard Arctic and Antarctic ice conditions. The targeted project, even though being fairly long with worldwide expertise on a university network, can only properly cover a few of the topics and those areas the development happens slowly need further great efforts. The authors hope, however, that the review given in this paper can enable planning of the future activities on this very important research area.

Declaration of competing interest

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

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