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A Framework for Integrating Life-Safety and Environmental Consequences into Conventional Arctic Shipping Risk Models

Thomas Browne [1,2,*], Rocky Taylor [1], Brian Veitch [1,*], Pentti Kujala [3], Faisal Khan [1] and Doug Smith [1]

1 Faculty of Engineering and Applied Science, Memorial University of Newfoundland, St. John's, NL A1B 3X5, Canada; rstaylor@mun.ca (R.T.); fikhan@mun.ca (F.K.); d.smith@mun.ca (D.S.)
2 Ocean, Coastal and River Engineering Research Centre, National Research Council of Canada, St. John's, NL A1B 3T5, Canada
3 Department of Mechanical Engineering, Aalto University, 02150 Espoo, Finland; pentti.kujala@aalto.fi
* Correspondence: thomas.browne@mun.ca (T.B.); bveitch@mun.ca (B.V.)

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Featured Application: A risk assessment framework that supports Arctic voyage planning and real-time operational decision-making through assignment of operational criteria based on the likelihood of ice-induced damage and the potential consequences.

Abstract: The International Code for Ships Operating in Polar Waters (Polar Code) was adopted by the International Maritime Organization (IMO) and entered into force on 1 January 2017. It provides a comprehensive treatment of topics relevant to ships operating in Polar regions. From a design perspective, in scenarios where ice exposure and the consequences of ice-induced damage are the same, it is rational to require the same ice class and structural performance for such vessels. Design requirements for different ice class vessels are provided in the Polar Code. The Polar Operational Limit Assessment Risk Indexing System (POLARIS) methodology provided in the Polar Code offers valuable guidance regarding operational limits for ice class vessels in different ice conditions. POLARIS has been shown to well reflect structural risk, and serves as a valuable decision support tool for operations and route planning. At the same time, the current POLARIS methodology does not directly account for the potential consequences resulting from a vessel incurring ice-induced damage. While two vessels of the same ice class operating in the same ice conditions would have similar structural risk profiles, the overall risk profile of each vessel will depend on the magnitude of consequences, should an incident or accident occur. In this paper, a new framework is presented that augments the current POLARIS methodology to model consequences. It has been developed on the premise that vessels of a given class with higher potential life-safety, environmental, or socio-economic consequences should be operated more conservatively. The framework supports voyage planning and real-time operational decision making through assignment of operational criteria based on the likelihood of ice-induced damage and the potential consequences. The objective of this framework is to enhance the safety of passengers and crews and the protection of the Arctic environment and its stakeholders. The challenges associated with establishing risk perspectives and evaluating consequences for Arctic ship operations are discussed. This methodology proposes a pragmatic pathway to link ongoing scientific research with risk-based methods to help inform recommended practices and decision support tools. Example scenarios are considered to illustrate the flexibility of the methodology in accounting for varied risk profiles for different vessel types, as well as incorporating input from local communities and risk and environmental impact assessments.

Keywords: arctic shipping; POLARIS; risk assessment; consequence modeling; life-safety; environmental safety; operations management

1. Introduction

Ships and crews operating in Arctic and Antarctic environments are exposed to a number of unique risks. The presence of sea ice and icebergs can impose additional loads on the hull, propulsion system, and appendages of a vessel. Cold temperatures, poor weather, and marine icing may reduce the effectiveness of components of the ship, ranging from deck machinery and emergency equipment to sea suctions. A relative lack of good charts, communication systems, and other navigational aids in the Polar regions, and the remoteness of these areas, makes rescue and clean-up operations difficult and costly.

Arctic maritime operations are complex socio-technical systems [1–4]. Not only are the vessels and crews exposed to risks, but the environment and local communities will be impacted by the consequences of shipping. In this regard, there are socio-economic aspects to Arctic shipping that should be appreciated. Holistic risk assessment frameworks and operational decision support tools should account for the needs and interests of the diverse stakeholders within these regions.

The Polar Code [5], adopted by the International Maritime Organization (IMO) and entered into force in 2017, addresses many of the design and operational challenges associated with marine transportation in the Arctic and Antarctic. It provides guidance on ship design, construction, equipment, operations, training, search and rescue, and environmental protection. The Polar Code also provides the Polar Operational Limit Assessment Risk Indexing System (POLARIS), an operational decision support tool that provides guidance on the operational limits of a vessel as a function of the vessel's ice class and observed or forecasted ice conditions [6].

The Polar Code was created, in part, in response to recommendations from the Artic Council's 2009 Arctic Marine Shipping Assessment report [7,8]. Recommendations include the need to enhance Arctic marine safety and the need to protect Arctic people and the environment.

A recent study of the negative impacts of ship activity on Arctic marine mammals notes a lack of maritime guidance for the management of environmental impacts of Arctic shipping [9]. For example, operational decision-support tools should account for region-specific environmental vulnerabilities to oil spills [10].

The current POLARIS methodology accounts for the likelihood of a vessel to incur ice-induced damage, but it does not properly account for the potential consequences resulting from the ice-induced damage event. The operational limitations for a vessel in ice should be assessed based on a risk profile that incorporates life and environmental consequences.

The risk-based design methods employed in the International Standard for Arctic Offshore Structures, 19906 [11] provide an approach to the treatment of life and environmental safety. A similar approach may be adapted for ships operating in ice environments. Such an approach would explicitly consider the number of persons on board (POB), the cargo being transported, regional aspects, and the operational exposure with respect to life-safety, environmental, and socio-economic consequences.

It is noted that while significant progress has been made in developing probabilistic ice load models to link vessels' ice exposure, extreme ice loads, and ice class selection [12–16], design aspects are outside the scope of the operationally focused work presented here.

The methodology presented in this paper draws from both the Polar Code and the International Organization for Standardization (ISO) 19906 to explore ways in which life-safety and environmental safety considerations employed in ISO 19906 for offshore structures can be applied to ice class ships operating in the Arctic and Antarctic regions.

A new risk assessment framework is presented that augments the current POLARIS methodology to model consequences. The framework accounts for the likelihood of incurring ice-induced damage and the potential life-safety, environmental, and socio-economic consequences.

The benefit of the proposed framework is that it builds on the current POLARIS methodology, providing operational guidance considering the potential severity of consequences. When the perceived risk of operating in ice increases, additional operational restrictions are imposed to maintain an equivalent safety level. The objective of the framework is to enhance Arctic marine safety and the protection of the Arctic environment and its stakeholders by supporting operational decision-making for ships operating in Polar regions.

The current POLARIS methodology was published as "interim guidance", to be updated based on experience gained after several years of use [6]. The proposed framework can be seen as a recommended modification to the current POLARIS methodology.

Section 2 compares the design code philosophies of the Polar Code and ISO 19906. Section 3 reviews the challenges associated with evaluating life-safety and environmental consequences of Arctic shipping. Section 4 introduces the proposed life-safety and environmental consequence framework. Section 5 provides scenarios to illustrate the flexibility of the methodology in accounting for varied risk profiles and different vessel types and cargos. In Section 6, the framework is applied to a benchmark case study incorporating data from published Arctic marine shipping assessments. Section 7 discusses the merits of the proposed framework and areas for future work. Section 8 is the conclusion.

2. Background

2.1. Design Code Philosophy: Ships vs. Structures

The goal of ice class ship design rules is to provide a vessel design that satisfies specified standards. The vessel design, including structure, propulsion systems, and auxiliary systems, is assessed against a range of specific conditions, such as ice, low temperatures, and high latitude, as well as the potential need to abandon the ship onto ice or land. As a result, ice class rules tend to be more prescriptive than performance-based. Vessel class is selected to satisfy the operational profile specified by the owner and the owner/operator is then responsible for safely operating the vessel within the bounds of its capabilities.

In comparison, offshore structure codes use a risk-based approach focused on ensuring target safety levels are achieved. The reliability of the asset depends, in part, on exposure levels, which are determined based on an assessment of the potential life-safety, environmental, and economic consequences associated with a particular installation. The structure is designed to safely withstand the site-specific environmental conditions and other operational requirements that it is expected to encounter over its design life. Support activities, such as ice management, may be carried out as part of routine operations to help ensure safety.

Presently, there is no direct account for life safety class and environmental safety class in shipping codes. Adopting exposure levels, similar to those used in the design of offshore structures, is a rational approach for incorporating life-safety, environmental, and socio-economic consequences in the operational decision making of ice class vessels.

2.2. IMO Regulations

The International Convention for the Safety of Life at Sea (SOLAS) [17] promotes safety of life at sea through design and construction, requirements for onboard lifesaving appliances, and operational guidelines and restrictions. Structurally, a ship is considered safe if it has sufficient strength, integrity, and stability. Operationally, communication, planning, and procedures play important roles in life safety and safe navigation, including regulations and guidelines addressing voyage planning, ships' routing and reporting system requirements, and vessel traffic services.

The International Convention for the Prevention of Pollution from Ships (MARPOL) [18] promotes the prevention of operational and accidental pollution from ships. Pollution by oil and other substances as a result of a marine accident is primarily mitigated through structural design and equipment requirements. Certain ship types may have more stringent design requirements depending on the type and quantity of cargo. Operational requirements primarily focus on controlling pollution from intentional, operational discharges or routine operations such as ship-to-ship transfer of crude oil.

From an operational risk management perspective, the procedures prescribed in SOLAS and MARPOL are broadly applied across a range of ship types.

2.3. Polar Code and POLARIS

The Polar Code was developed, in part, to address the demands associated with the operation and navigation of ships in Polar regions that are not sufficiently captured in the existing requirements outlined in SOLAS and MARPOL. The Polar Code covers the full range of design, construction, equipment, operations, training, search and rescue, and environmental protection matters relevant to ships operating in the inhospitable waters surrounding the two poles.

Vessels being designed for operation under the Polar Code are required to undergo an operational assessment to establish the vessels' operational capabilities and limitations. The operational assessment follows the risk-based IMO Formal Safety Assessment [19], which forms the basis for a vessel's Polar Ship Certificate and Polar Waters Operational Manual (PWOM), and implicitly incorporates crew and environmental safety. In this regard, the Polar Code works well for vessel design and class selection.

For voyage planning and real-time decision making on the bridge, the POLARIS methodology assesses the operational limitations of an ice class vessel. POLARIS was developed, in part, from experiences gained through use of Canada's Arctic Ice Regime Shipping Systems (AIRSS) and the Russian Ice Certificate. POLARIS evaluates the risks posed to a ship operating in ice based on assigned ice class and the ice regime. The ice regime may be historic or forecasted in the case of voyage planning, or it may be observed from the bridge of the ship in the case of real-time decision-making.

For a given vessel class, POLARIS assigns Risk Index Values (RIVs) corresponding to each ice type, where a given ice regime can be comprised of several different ice types. The total Risk Index Outcome (RIO) is determined by the summation of the RIVs for each ice type present in the ice regime multiplied by the corresponding concentration of that ice type (expressed in tenths), as shown in Equation (1):

$$\mathrm{RIO} = (\mathrm{C1} \times \mathrm{RIV1}) + (\mathrm{C2} \times \mathrm{RIV2}) + \cdots + (\mathrm{Cn} \times \mathrm{RIVn}) \tag{1}$$

where C1 ... Cn = concentration (in tenths) of each ice type within the ice regime and RIV1 ... RIVn = the corresponding RIVs for each ice type.

The calculated RIO governs the operational criteria for the vessel: 'Normal operation' ($\mathrm{RIO} \geq 0$), 'elevated operational risk' ($-10 \leq \mathrm{RIO} \leq 0$), or 'operation subject to special consideration' ($\mathrm{RIO} < -10$). Response measures for 'elevated operational risk' include reducing speed, additional watch keeping, or icebreaker escort, while 'operation subject to special consideration' measures include further reduction of speed, course alteration, or other special measures to reduce risk. Guidance on procedures for operational criteria should be documented in the vessel's PWOM.

The POLARIS methodology was recently validated as a suitable means for assessing the risk of structural damage of ice-going vessels [12]. Two vessels were instrumented to record full-scale ice-induced hull loads and ice concentrations during their voyages. POLARIS was used to determine the optimal ice class to allow navigation in both scenarios. Optimal ice class was also evaluated based on the required hull strength to mitigate the risk of structural damage. For each scenario, POLARIS identified the same optimal ice class as the structural risk analysis.

Despite the Polar Code promoting a holistic approach to risk management, POLARIS is not a single solution for operational risk management; it only accounts for the risk of structural damage. There is no consideration for the potential consequences of a ship damaged by ice. Operators require complementary tools and additional data to support a more holistic, risk-based decision-making process [20].

The intent of POLARIS is that the operational criteria for a vessel in a given ice regime corresponds to the operational capabilities of the vessel's ice class. In effect, a high ice class vessel operating in heavy ice will have a similar perceived risk level as a non-ice strengthened vessel in open water [21]. However, there is significant uncertainty in estimated ice loads for different ice–ship interaction scenarios [12]. POLARIS does not guarantee safe navigation and incidents can still occur. Life-safety and environmental consequences that can result from ice damage to a vessel need to be accounted for in operational decision-making.

2.4. ISO 19906 Life-Safety Classes, Consequences, and Exposure

The risk-based approach employed by ISO 19906 for the design of Arctic offshore structures specifies that the reliability of a structure should reflect its exposure level with respect to life-safety, environmental, and economic consequence categories. For a given exposure level, extreme and abnormal level environmental loads corresponding to specified exceedance probabilities are determined. Calibrated action and material/resistance factors are then applied to determine the design actions corresponding to structural limit states specified in the code.

In ISO 19906, the life-safety category of an asset takes into consideration the safety of personnel and the probability of a safe evacuation. Three life-safety categories are defined for Arctic offshore structures: S1 (manned non-evacuated), S2 (manned evacuated), S3 (unmanned).

Similarly, the consequence category of an asset takes into consideration the potential risks in relation to the safety of personnel responding to an incident, environmental damage, and economic loss. Three consequence categories are defined in ISO 19906 for Arctic offshore structures: C1 (high consequence), C2 (medium consequence), C3 (low consequence).

The exposure level of an asset is then determined as a function of the assessed life-safety and consequence categories. Table 1 is used to determine the exposure level as a function of life-safety categories and consequence categories [11].

Table 1. Determination of exposure level (based on International Organization of Standardization (ISO) 19906 [11]).

Life-Safety Category	Consequence Category		
	C1 High	**C2 Medium**	**C3 Low**
S1: manned non-evacuated	L1	L1	L1
S2: manned evacuated	L1	L2	L2
S3: unmanned	L1	L2	L3

Manned non-evacuated (S1) refers to Arctic offshore structures in which there is no planned evacuation of personnel prior to a forecasted design environmental loading event. Manned evacuated (S2) refers to a platform in which evacuation of personnel prior to a forecasted design environmental loading event is planned. Unmanned (S3) refers to a platform that is not normally manned [11].

For offshore structures, the life-safety and consequence categories and corresponding exposure levels are defined during the design process and influence the structural capacity of the design to achieve target safety levels. The application proposed here is for management of operational risk of Arctic ships. When the perceived risk of operating a vessel in ice is increased, additional operational restrictions are required to maintain an equivalent risk level.

2.5. Linking Risk-Based Approach and Polar Rules

Concerning Arctic marine transport, the number of people on board, the amount and type of potential pollutants being transported, and the characteristics of the operating region directly impact a vessel's risk exposure and the severity of consequences. It is logical to account for these higher and lower risk levels in the rules. From an operational standpoint, an approach that explicitly reflects life-safety, environmental, and socio-economic consequences in a risk-based framework is needed.

The Polar Code works well for vessel design and class selection, but a more explicit approach that reflects life-safety and environmental/socioeconomic consequences in a risk-based framework is needed. A risk-based framework can be linked to the operational limitations of the vessel to support decision-making (i.e., POLARIS).

3. Arctic Shipping Risk

3.1. Life-Safety and Environmental Consequences

Evaluating life-safety and environmental consequences related to Arctic shipping risks is challenging. A lack of accident data and experience limits the application of conventional risk approaches that rely on empirical event probabilities and quantified consequence severities. Alternative, unconventional risk assessments are necessary.

Marchenko et al. [22] used qualitative, expert-based risk analysis of ship accidents to establish risk levels for a range of vessel types and incidents in various regions of the Arctic. They established that the perceived likelihood of high consequence events increases with increasing vessel traffic, the number of passengers, and the presence of hazardous cargos. They highlighted that the severity of life-safety and environmental consequences can escalate in the Arctic due to a lack of emergency response resources and the harsh environmental conditions.

Oil spills are the dominant threat posed by Arctic shipping [8] but evaluating environmental consequences is complex. The presence of dangerous goods onboard a vessel introduces the risk of environmental damage, but the consequence severity is not simply a product of accident potential and oil spill trajectory [23]. An evaluation of environmental risk from an oil spill should consider habitat exposure areas, recovery potentials of species and habitats, and the current state of the habitats [23,24]. Nevalainen et al. [25] go further, suggesting that risk assessments must consider the entire ecosystem (rather than species-specific) to identify long-term impacts and provide a holistic understanding of the impacts of an oil spill. Given the complexity of Arctic oil spills, evaluating oil spill risk requires multidisciplinary expert knowledge and region-specific analyses.

Evaluating life-safety consequences of Arctic shipping is also complex, with many dynamic factors (spatial and temporal). The number of passengers and crew on board a vessel and the ability to mount safe and effective escape, evacuation, and rescue (EER) will influence the severity of potential life-safety consequences. The rescue of crew and passengers is daunting: Limited regional search and rescue capabilities, scarce and aging infrastructure, long response times, and inadequate emergency response capacities for large-scale incidents (e.g., large cruise vessels present a high life-safety risk in the Arctic) [22,26,27].

Risk-based operational decision-making for ice class vessels should be based on a careful consideration of all consequences and the integration of multidisciplinary knowledge. Evaluating the severity of environmental and life-safety consequences is complex with many dynamic factors. The framework proposed here integrates multidisciplinary knowledge for scenario-based risk management for ships operating in ice.

3.2. Risk Perspectives and Applications

Different risk perspectives and applications have implications on risk acceptance and operational decision making. Aven et al. [28] remind us that there is a broad range of complex risk perspectives, and risk-based decision-making should aim to incorporate the full range of stakeholders and their diverse perspectives on risk and consequence (e.g., scientific, economic, social, and cultural).

Goerlandt and Montewka [29] examined a range of risk definitions and perspectives that have been applied in maritime transportation. Based on this, it can been seen that the risk definition adopted in POLARIS accounts for the likelihood of an undesirable event (i.e., the vessel incurring ice damage), but does not account for the relevant consequences of that event. The framework proposed here aims to complement POLARIS by accounting for the severity of consequences resulting from an ice damage event.

Similar foundational issues are present in oil spill risk analysis. Parviainen et al. [30] provided context on the ambiguity in risk perspectives and risk governance related to oil spills in the Barents Sea. Through the development of qualitative mental models for various stakeholders, they demonstrated there are multiple ways in which stakeholders define and understand risk, but existing risk assessment and management practices do not reflect this broad range of perspectives.

Further adding to the complexity of assessing Arctic shipping risk is the treatment of uncertainty, or strength of evidence. Risk analysis for maritime transportation seldom incorporates an assessment of uncertainty [1,29] despite the implications it has on risk acceptance and decision making.

The lack of experience and data for Arctic operations has made expert elicitation a common approach to risk. Expert judgement introduces additional uncertainties and bias that need to be considered and communicated to decision makers [30,31].

There are also "black swan" events [4,22,32]. These are rare or surprising events with the potential for severe or extreme consequences that are not captured in traditional risk analyses. As Arctic shipping activity increases and high risk exposure vessels enter new geographic regions, "black swan" events should be considered.

Several recent studies have proposed operational risk frameworks for ships in ice with a variety of risk perspectives and applications. Bayesian networks are a common risk assessment methodology applied to Arctic shipping. They allow the integration of quantitative and qualitative (e.g., expert knowledge) data and a means of quantifying uncertainty. Montewka et al. [33] used empirical data sets and Bayesian networks to assess ship performance (speed) as a function of ice conditions. Such a model supports operational risk management to avoid besetting in ice and to manage fuel economy. Fu et al. [34] adopted a Bayesian Belief Network using empirical data supplemented with expert judgement to assess the risk influencing factors leading to ship besetting.

Bergstrom et al. [35] investigated goal- and risk-based design to assess the performance of ships operating in ice. The ship is treated as a subcomponent of a larger Arctic marine transport system, utilizing principles of system-based design. While their intent was to incorporate a risk-based assessment of system performance at the design stage, their systems thinking approach has merit for the scenario-based framework proposed here.

Smith et al. [2] used the Functional Resonance Analysis Method (FRAM) to model Arctic ship navigation as a complex system and analyze the system functions (human, technical, and organizational) that influence ship performance. While FRAM is not a risk assessment methodology, it promotes a holistic understanding of system dynamics that can support real-time risk-based decision making.

Figure 1 summarizes the range of factors and foundational issues that should to be considered in the evaluation of consequences of Arctic shipping.

The risk framework proposed here aims to establish a risk perspective that captures the needs and interests of the diverse stakeholders of Arctic shipping, and to move towards more holistic risk management practices.

Figure 1. The factors and foundational issues that influence the evaluation of Arctic shipping consequences.

4. Proposed Life-Safety and Environmental Consequence Framework

The premise of the proposed life-safety and environmental consequence framework is that if you have two ships with the same ice class in the same ice conditions, a vessel having higher potential consequences for life-safety and/or environmental safety should be operated more conservatively. While two scenarios may have the same structural ice risk, when consequence severities are considered, the overall risk may be higher or lower and this should be reflected in the required operating limits.

Figure 2 shows the chain of consequences considered in the risk framework presented here. In the event the structural capacity of a ship's hull is exceeded, operational intervention measures will be employed to mitigate consequences. Should these measures be inadequate, EER may be required, which may have life-safety impacts, and there is the potential for a spill, which may have ecological and socio-economic impacts.

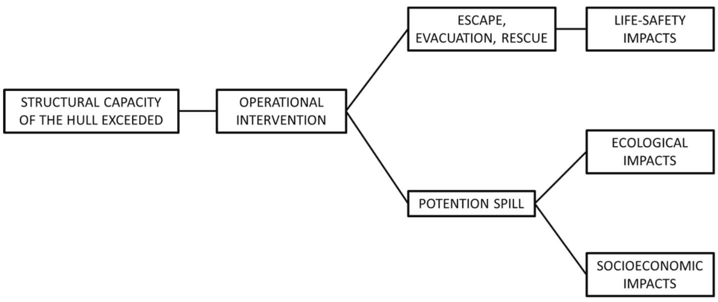

Figure 2. The chain of consequences following ice damage to a vessel considering life and environmental safety.

4.1. Overview of Methodology

Ship design, class selection, and performance criteria already follow well-established methodologies that are defined in the Polar Class rules. The approach proposed here is to add an exposure adjustment term in the POLARIS methodology that reflects the higher consequence operations. It will also provide a mechanism to recognize measures taken by vessel owners and operators for reducing risk. This is relevant for unmanned/autonomous vessels that do not carry pollutants, as such vessels could be operated more aggressively in a given ice regime with no impact to life-safety or the environment.

Following a similar approach to that used in ISO 19906, a life-safety category and an environmental/socio-economic consequence category is used to inform the assessment of a vessel's exposure level. The exposure level corresponds to an RIV adjustment factor, similar to the current approach in POLARIS for the treatment of seasonal ice decay. In doing so, the proposed framework guides the formulation of a RIO corresponding to the magnitude of life-safety, environmental, and socio-economic risks and consequences.

4.2. Life-Safety Categories

The proposed risk assessment starts with identification of the life-safety category of a ship, which is a ranking that reflects its exposure in relation to the safety of crew and passengers. It could also reflect the response plan adopted by the vessel and emergency response capacities along the planned route. As an example, the life-safety categories may be divided into four ranges based on POB, as defined in Table 2.

Table 2. Life-safety categories.

Life-Safety Category	Persons on Board (POB) Range
S1: high life-safety	POB > 500
S2: moderate life-safety	50 < POB ≤ 500
S3: low life-safety	0 < POB ≤ 50
S4: unmanned / autonomous	POB = 0

These life-safety categories are not equivalent to those provided in ISO 19906. ISO 19906 assesses life-safety for Arctic offshore structures based on site-specific, risk-based, designed EER strategies. It is recognized that factors influencing life-safety for ships transiting the Arctic (e.g., emergency response capacities and times, and environmental conditions) will vary spatially and temporally. The life-safety categories in Table 2 are intended to reflect the scale of search and rescue response operations required to assist in an emergency. More emergency response resources are required to ensure a safe response for vessels with higher numbers of POB. The categories provided here are used for illustrative purposes.

4.3. Environmental/Socio-Economic Consequence Categories

The next aspect of the proposed method is assessment of the environmental and socio-economic consequence categories associated with the vessel and its planned route. Consequences to be considered may be grouped into region-specific sensitivities, as well as vessel-specific considerations relating to the amount and type of potential pollutants.

Regulators and government agencies will be responsible for developing policies for Arctic maritime safety. Policy decisions will need to be informed by many different types of knowledge, such as multidisciplinary risk analyses, stakeholder engagements, and collaborative mapping. While a detailed discussion of risk-based policy development is beyond the scope of the present work, there are important links to the methodology proposed here. It is possible for environmental risk information to be communicated through geo-spatial maps, similar to those in the Arctic Council's report on the identification of Arctic marine areas of heightened ecological and cultural significance [24]. Such maps can be used to inform operational decision making and route planning.

Proposed approaches for capturing and categorizing these different types of consequences are described below.

4.3.1. Protection Status Relating to Socio-Economic Considerations

In the context of the proposed consequence category risk framework, regions of particular socio-economic value (e.g., local areas of high cultural significance, high significance to traditional activities, with designated special status such as United Nations Education, Science, and Cultural Organization (UNESCO) sites, etc.) could be mapped as having a particular Protection (P) category designation. Such information would indicate areas of high, moderate, and normal status (Table 3).

Table 3. Socio-economic protection categories.

Protection Status	Assigned Value
High	P = 3
Moderate	P = 2
Normal	P = 1

These regions can be geographically defined and easily communicated to operators in an automated fashion, including any special operating considerations required of vessels in these areas. Such an approach will help streamline regulatory implementation and inform operational planning and decision-making. Figure 3 illustrates how geographically referenced maps can be used to communicate regions with socio-economic protection status.

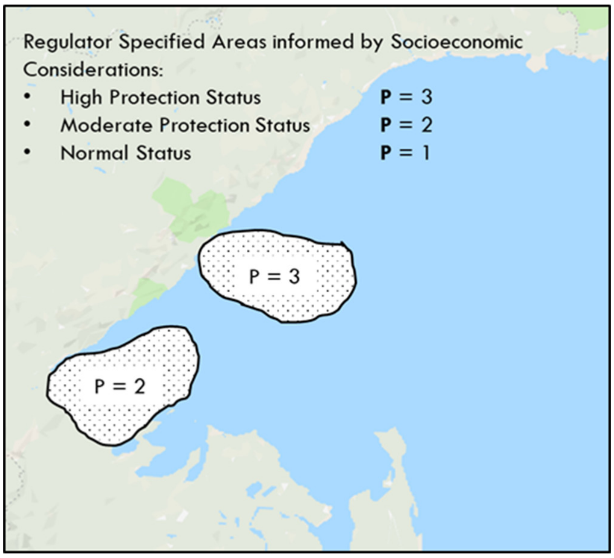

Figure 3. Examples of geographic regions defined as requiring socio-economic protection status.

4.3.2. Ecological Sensitivity Categories

Through ecological risk assessments and marine environmental assessments, it is possible to model and assess the sensitivity of different species and populations to identify the ecological sensitivity of geographic regions. Based on ecological characteristics (e.g., endangered species, nesting colonies, seasonal migrations, etc.), regions could be mapped as having ecological sensitivity (E) category designations that would indicate areas of high, moderate, and normal ecological sensitivity (Table 4). Policy information can be communicated in a similar fashion as proposed for regions requiring socio-economic protection status (Figure 3), including any special operating requirement for vessels in these regions.

Table 4. Ecological sensitivity categories.

Ecological Sensitivity Category	Assigned Value
High	E = 3
Moderate	E = 2
Normal	E = 1

4.3.3. Spill Consequence Categories

The spill risk for a given vessel will depend on the amount and type of potential contaminant carried onboard. Through oil spill risk assessments, vessels could be identified as having high, moderate, or normal levels of potential spill consequence (SC), as presented in Table 5. For example, chemical tankers carrying large volumes of hazardous liquids would be categorized as having a high SC value, while a smaller vessel with limited fuel (or that uses a more environmentally friendly fuel) may be assigned a lower SC value.

Table 5. Spill consequence categories for vessels.

Spill Consequence	Assigned Value
High	SC = 3
Moderate	SC = 2
Normal	SC = 1

As with other categories, regulators can specify what, if any, special operating considerations are required for higher spill consequence vessels.

4.3.4. Protection Status, Ecological Sensitivity, and Spill Consequence Index (PESCI)

The different consequence categories are combined to inform an operational exposure level. The process is referred to as the Protection Status, Ecological Sensitivity, and Spill Consequence Index (PESCI) method. A PESCI value is dependent on the socio-economic protection status (P) and ecological sensitivity (E) categories for the region, and the spill consequence category (SC) for the vessel. PESCI values are assigned in accordance with Table 6a,b,c, which corresponds to socio-economic protection category values (P) of 1, 2, and 3, respectively.

Table 6. PESCI values.

a. PESCI Values (P = 1)				
	3	2	3	4
SC	**2**	1	2	3
	1	0	1	2
		1	**2** **E**	**3**

b. PESCI Values (P = 2)				
	3	3	4	5
SC	**2**	2	3	4
	1	1	2	3
		1	**2** **E**	**3**

c. PESCI Values (P = 3)				
	3	4	5	6
SC	**2**	3	4	5
	1	2	3	4
		1	**2** **E**	**3**

The PESCI value corresponds to an overall consequence category of high (C1), moderate (C2), or normal (C3), in accordance with Table 7.

Table 7. Consequence categories.

Consequence Category	PESCI Range
C1: high consequence	PESCI ≥ 3
C2: moderate consequence	1 < PESCI < 3
C3: normal consequence	PESCI ≤ 1

4.4. Operational Exposure Levels

The next step is determination of the operational exposure level, which is dependent on the life-safety and consequence categories, as detailed in Table 8. For example, ships with high life-safety (S1) are designated the highest operational exposure level (L1); ships with a moderate life-safety (S2) and a consequence category of high (C1), moderate (C2), or low (C3) are designated an operational exposure level of L1, L2, or L3, respectively.

Table 8. Operational exposure levels.

Life-safety Category	**S1** (high)	L1	L1	L1
	S2 (moderate)	L1	L2	L3
	S3 (low)	L1	L3	L3
	S4 (unmanned)	L2	L4	L4
		C1 (high)	**C2** (moderate)	**C3** (low)
			Consequence Category	

4.5. RIV Adjustment for Exposure Levels

Finally, the proposed approach is incorporated into the existing POLARIS methodology through adjustment of the calculated RIVs, based on the determined operational exposure level. This is similar to the existing method to account for observed seasonal ice decay in POLARIS. RIV adjustment factors corresponding to operational exposure levels are presented in Table 9.

Table 9. Risk Index Value (RIV) adjustment factors for operational exposure levels.

Operational Exposure Level	**RIV Adjustment Factor**
L1	$RIV_{L1} = -2$
L2	$RIV_{L2} = -1$
L3	$RIV_{L3} = 0$
L4	$RIV_{L4} = +1$

Once the RIV adjustment factor is identified, a modified RIO is calculated following Equation (2).

$$RIO_{modified} = C1 \times (RIV1 + RIV_L) + C2 \times (RIV2 + RIV_L) + \cdots + Cn \times (RIVn + RIV_L) \quad (2)$$

where C1 ... Cn = concentration (in tenths) of each ice type within the ice regime, RIV1 ... RIVn = the corresponding standard RIVs for each ice type (following POLARIS); and RIV_L = the RIV adjustment factor.

The modified RIO is then used as the basis for the selection of one of three levels of operation, as per POLARIS: 'Normal', 'elevated operational risk', or 'operations subject to special consideration'. The overall process of the proposed risk assessment framework is presented in Figure 4.

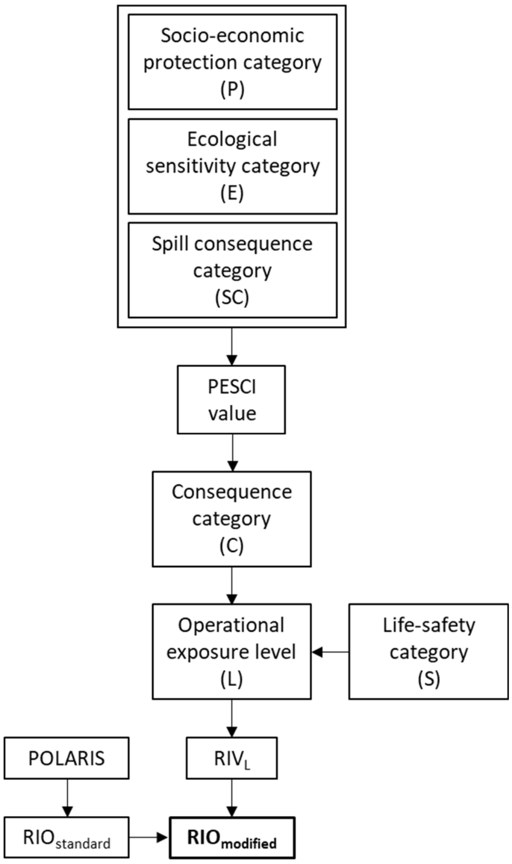

Figure 4. Risk assessment framework process.

5. Illustrative Example

To demonstrate the application of the proposed risk assessment framework and its impact on voyage planning and navigation, a fictitious waterway was considered (Figure 5).

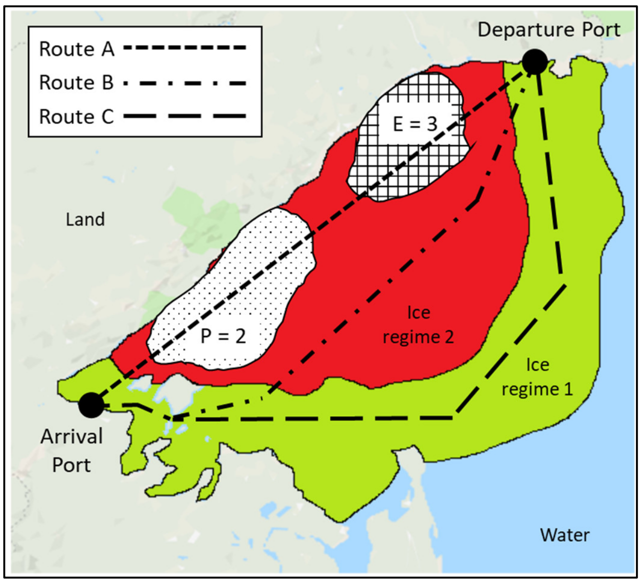

Figure 5. Waterway and routes for illustrative example.

Within the waterway, two regions were classified as having special ecological and socio-economic designations. The crosshatched region to the north was assigned a high ecological sensitivity category

(E = 3). To the south, the stippled region was assigned a moderate socio-economic protection status category (P = 2). Outside the regions of heightened environmental sensitivity, the ecological sensitivity and socio-economic protection category values were low (E = P = 1).

The operational exposure for five different vessels was assessed along three different routes. Based on the assessed risk level and resulting operational criteria, the optimal route for each vessel was identified.

5.1. Route Identification

The planned voyage departed from a northern port and arrived at a port in the south, as depicted in Figure 5. Two different ice regimes were present. The ice types and associated concentrations for each ice regime are presented in Table 10.

Table 10. Ice regimes for illustrative example.

Ice Regime	Ice Type	Concentration
Ice Regime 1	Thin First Year	$5/10^{th}$
	Grey Ice	$4/10^{th}$
	Open Water	$1/10^{th}$
Ice Regime 2	Thick First Year	$8/10^{th}$
	Thin First Year	$1/10^{th}$
	Open Water	$1/10^{th}$

Three different route options were available to transit from the departure port to the arrival port. Route A was the shortest distance, transiting along the coast through the more severe ice conditions (ice regime 2) and through the regions with heightened environmental sensitivity. Route B transited farther from the coast to avoid the regions of heightened sensitivity but remained in the more severe ice conditions. Route B was a longer distance than Route A. Route C was the longest distance, transiting the farthest from the coast to remain in the less severe ice conditions (ice regime 1).

Any vessel navigating through this waterway must acknowledge the ice regimes and the regions of heightened ecological and socio-economic sensitivity. The proposed risk assessment framework accounted for this and guided the decision on operating criteria for a given vessel.

5.2. Vessel Scenarios

To demonstrate the impact of the life-safety category and the spill consequence category, five different vessels were selected: A bulk carrier, an oil tanker, a cruise ship, a fishing vessel, and an autonomous ship. The vessel ice class, POB, associated life-safety category, and spill consequence value for each vessel is provided in Table 11.

Table 11. Vessel details for illustrative example.

Vessel Type	Ice Class	POB	Life-Safety Category	Spill Consequence Category
bulk carrier	PC5	55	S2	SC = 2
oil tanker	PC5	75	S2	SC = 3
cruise ship	PC5	2500	S1	SC = 1
fishing vessel	PC5	12	S3	SC = 1
autonomous	PC5	0	S4	SC = 1

The bulk carrier, with a crew of 55, had a moderate life-safety category (S2) and a moderate spill consequence (SC = 2). The oil tanker had a high spill consequence category (SC = 3) and a moderate life-safety category (S2). The cruise ship, with the highest number of passengers at 2500, received a high life-safety category (S1), but a low spill consequence (SC = 1). The fishing vessel had both a low life-safety category (S3) and a low spill consequence (SC = 1). The autonomous ship had an unmanned life-safety category (S4) and a low spill consequence (SC = 1). All vessels had an assigned ice class of PC5.

5.3. Results

In this example, four regions required separate risk assessments to evaluate and compare the routes. The four regions were ice regime 1, ice regime 2, the high ecologically sensitive region, and the moderate socio-economic protected status region. Three possible routes were considered here:

- Route A passed through all four regions and required assessment of each region.
- Route B avoided the regions of heightened environmental sensitivity and needed only to be assessed for both ice regimes.
- Route C passed only through ice regime 1.

The risk assessment results for each vessel in each of the four regions are presented in Table 12.

Table 12. Risk assessment results for the illustrative example.

Region	Vessel Type	PESCI	C	L	RIV_L	RIO (std)	RIO (mod)
Ice Regime 1 E = 1, P = 1	bulk carrier	1	C3	L3	0	25	**25**
	oil tanker	2	C2	L2	−1	25	**15**
	cruise ship	0	C3	L1	−2	25	**5**
	fishing vessel	0	C3	L3	0	25	**25**
	autonomous	0	C3	L4	1	25	**35**
Ice Regime 2 E = 1, P = 1	bulk carrier	1	C3	L3	0	5	**5**
	oil tanker	2	C2	L2	−1	5	**−5**
	cruise ship	0	C3	L1	−2	5	**−15**
	fishing vessel	0	C3	L3	0	5	**5**
	autonomous	0	C3	L4	1	5	**15**
High Ecological Sensitivity E = 3, P = 1	bulk carrier	3	C1	L1	−2	5	**−15**
	oil tanker	4	C1	L1	−2	5	**−15**
	cruise ship	2	C2	L1	−2	5	**−15**
	fishing vessel	2	C2	L3	0	5	**5**
	autonomous	2	C2	L4	1	5	**15**
Moderate Socio-economic Sensitivity E = 1, P = 2	bulk carrier	2	C2	L2	−1	5	**−5**
	oil tanker	3	C1	L1	−2	5	**−15**
	cruise ship	1	C3	L1	−2	5	**−15**
	fishing vessel	1	C3	L3	0	5	**5**
	autonomous	1	C3	L4	1	5	**15**

The standard RIOs (based on the current POLARIS methodology) were equivalent because the vessels had equivalent ice class (PC5). In ice regime 1 the standard RIO was 25 and in ice regime 2 the standard RIO was 5. This corresponded to an operational criterion of 'normal operations' in both ice regimes. The presence of regions with heightened environmental sensitivity did not impact the standard RIO.

The proposed risk assessment framework was applied to each vessel as described below.

5.3.1. Bulk Carrier

In ice regime 1, the bulk carrier received an overall consequence category C3 (normal) based on its moderate spill consequence value of 2. Combined with a moderate life-safety category S2, the bulk carrier was assigned an operational exposure level of L3 corresponding to an RIV adjustment factor of 0. The modified RIO was equivalent to the standard RIO. A similar result was observed for the bulk carrier in ice regime 2. The bulk carrier required no operational restrictions in ice regimes 1 or 2.

Due to the bulk carrier's moderate spill consequence value, the vessel received a modified RIO of −15 ('operation subject to special consideration') in the region of high ecological sensitivity. The bulk carrier should avoid operating in this region. In the region of moderate socio-economic sensitivity, the bulk carrier received a modified RIO of −5 ('elevated operational risk'). The bulk carrier may operate in this region with reduced speed, additional watching, or icebreaker escort.

The bulk carrier should avoid operating in the region of high ecological sensitivity due to the high operational exposure level. Route A was not an option. The bulk carrier can operate along Route B or C without any operational restrictions. Route B was the optimal choice as it is the shorter distance.

5.3.2. Oil Tanker

In ice regime 1, the oil tanker received a modified RIO of 15 ('normal operations'). In the more severe ice conditions of ice regime 2, the modified RIO was reduced to −5 ('elevated operational risk'). In both regions of heightened environmental sensitivity, the high spill consequence value of the oil tanker resulted in a modified RIO of −15 ('operation subject to special consideration').

The oil tanker should avoid Route A since operating in either of the environmentally sensitive regions imposes the strictest operational criteria. Navigation of the oil tanker along Route B would require reduced speeds, additional watch keeping, or icebreaker escort. Along Route C it could maintain 'normal operation' as this route had the lowest operational exposure.

Note that in the socio-economic protection status region, the moderate spill consequence category of the bulk carrier resulted in less restrictive operational criteria than the oil tanker (high spill consequence). This exemplified the impact of differences in spill consequence category on operating criteria.

5.3.3. Cruise Ship

In ice regime 1, the cruise ship received a modified RIO of 5 ('normal operations'). In ice regime 2 the cruise ship received a modified RIO of −15 ('operations subject to special consideration'), reflecting the severe life-safety consequences should an incident occur in this ice regime with 2500 passengers onboard. Due to the cruise ship's low spill consequence value, there was no additional consequence severity for operating in an environmentally sensitive zone. However, the modified RIO remained at −15 due to its high life-safety category in ice regime 2. Route C was the only option that allowed for 'normal operations' for a cruise ship of this size.

It is noted that the operational restrictions for the cruise ship would be much less severe if it were a smaller expedition cruise vessel with fewer than 500 people on board and/or if the vessel were built to a higher ice class.

5.3.4. Fishing Vessel

Due to the smaller numbers of POB, the fishing vessel fell within the S3 life-safety category. It is important to note that this designation was intended only to reflect the reduced scale of search and rescue response operations required to assist in an emergency for a vessel of this size compared to vessels with very large numbers of POB. Regardless of the life-safety category designation, adequate resources need to be in place to ensure safe operations and timely emergency response in *all* situations. This categorization should in no way be misinterpreted as placing different valuations on life-safety under different conditions. The correct interpretation here is that less emergency response resources are required to ensure a safe response for vessels with smaller numbers of POB than would be required to respond to vessels with larger numbers of POB.

Similarly, the low volumes of contaminants on board a smaller vessel, such as a fishing vessel, places it in a low spill consequence category. The goal in *all* cases is to prevent any potential environmental damage and minimize environmental impact. The designations proposed here reflect the fact that fewer resources would be required to respond to a potential environmental event and less ecological consequence would be expected for vessels that have lower spill consequence values.

For the fishing vessel, given its S3 and C3 designations, its operational exposure was assessed as low and its modified RIO was equivalent to the standard RIO. In the regions of ecological and socio-economic sensitivity, the fishing vessel received no adjustment to its operational criteria because its consequence severity was low. Normal operations can be maintained along any route. Route A was the optimal choice as it is the shortest distance.

5.3.5. Autonomous Vessel

The autonomous ship had an unmanned life-safety category and low spill consequence value. It received an RIV adjustment of +1. This increased the modified RIOs to 35 and 15 in ice regimes 1 and 2, respectively. The autonomous vessel can maintain normal operations along any route. Route A was the optimal choice as it was the shortest distance.

5.3.6. Comparison of Different Vessel Types

Having assessed all four regions in the waterway, we saw that regions of heightened environmental sensitivity only influence operational guidance to vessels with potentially higher spill consequence. This was, in turn, reflected in the viable route options available to each vessel type, as summarized in Table 13 below.

Table 13. Comparison of viable route options by vessel type.

Vessel Type	Route A	Route B	Route C
bulk carrier	'do not proceed'	'normal operations'	'normal operations'
oil tanker	'do not proceed'	'subject to special consideration'	'normal operations'
cruise ship	'do not proceed'	'do not proceed'	'normal operations'
fishing vessel	'normal operations'	'normal operations'	'normal operations'
autonomous vessel	'normal operations'	'normal operations'	'normal operations'

For the bulk carrier to maintain normal operations and not have to reduce its speed, it needed to avoid both the high ecologically sensitive region and the moderate socio-economic protected region. Route A was not an option.

The oil tanker should remain outside both environmentally sensitive regions. Route A was not an option. Route B was viable but required reduced speeds or other risk mitigation measures. Route C allowed for normal operations.

The large cruise ship was subjected to the most restricted operations as a result of its high life-safety category. To maintain normal operations, the cruise ship must select Route C. For cruise companies looking to build new vessels for operating in such regions, this information could play an important role in informing the selection of ice class and sizing new vessels, since smaller, higher ice class cruise ships would have greater operational range with fewer operability restrictions and lower costs for escort icebreakers.

The fishing vessel and autonomous vessel, given their lower life-safety and consequence categories, could proceed under normal operations along either Route 1 or Route 2. The autonomous vessel posed very low life-safety and environmental risk and was permitted to go into more severe ice conditions with less restrictions, should the owners wish to do so.

6. Benchmark Case Study

The example scenarios presented above are intended to illustrate the overall application of the framework. A benchmark case study is presented here to demonstrate the application of the proposed framework using inputs from Arctic marine shipping assessments. The case study considers a cruise vessel and an oil tanker navigating along the North West coast of Svalbard, Norway, during the summer season. Data to support the assignment of life-safety and environmental consequence categories were obtained from published Arctic marine risk assessments and environmental impact assessments.

Marchenko et al. [22] evaluated the life-safety risk for shipping in five different regions of the Arctic. Their evaluation was based on accident data, trends in ship activity, and expert knowledge elicitation. Consideration was given to regional dependencies, such as vessel traffic levels, environmental conditions, and private/government emergency response capacities. Risk matrices were developed for the five regions showing the frequency of different accident types for different vessels, and the severity of the consequences to human health.

Marchenko et al. [22] considered several accident types. For the purpose of this case study, focus was on damage by collision, recognizing that this captured collisions with ice as well as collisions with other ships or marine infrastructure. In the waters around Svalbard, cruise vessels are assessed as presenting a high life-safety risk (S1) and oil tankers are assessed as moderate (S2).

A relative spill consequence category for each vessel was assigned based on data from accidents with similar vessel types. The Exxon Valdez oil tanker spilled approximately 41,000 m^3 of crude oil after running aground off the coast of Alaska in 1989 [36]. The Motor Vessel (MV) Explorer cruise ship had approximately 210 m^3 onboard when it sank after striking an iceberg off the coast of Antarctica [37]. Based on these values, the oil tanker and the cruise ship were assigned relative spill consequence categories of high (SC = 3) and low (SC = 1), respectively.

The vessel-specific and environmental-specific consequence category values are presented in Table 14. For the purpose of this study, both vessels were assumed to have a Polar ice class of PC5.

Table 14. Vessel details for illustrative example.

Vessel Type	Ice Class	Life-Safety Category	Spill Consequence Category
cruise vessel	PC5	S1	SC = 1
oil tanker	PC5	S2	SC = 3

The Arctic Council [24] has reported areas of heightened ecological sensitivity throughout the Arctic, including around Svalbard. Their evaluation considers the impact of Arctic oil spills and other Arctic shipping-related threats on fish, bird, and mammal activities (e.g. migration, breeding, feeding, etc.). The regional sensitivities have a seasonal dependence. During the summer season, a large seabird breeding colony is present off the NW coast of Svalbard (Figure 6). This region is evaluated as having a high ecological sensitivity to oil spills (E = 3).

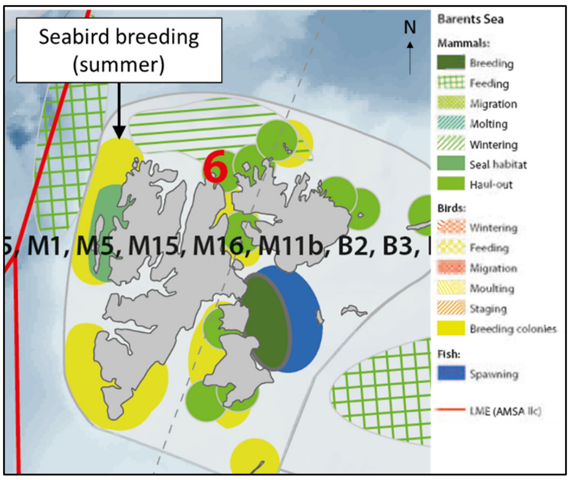

Figure 6. Areas of heightened ecological significance around Svalbard, Norway, (modified from Figure A.6 [24]).

The Arctic Council reported that the information necessary to evaluate culturally significant regions in the Arctic was not available at this time [24]. In the absence of this data, a default socio-economic protection category of low (P = 1) will be used for the purpose of this case study.

The ice conditions on 16 June 2019 were used for the case study, as reported by the Danish Meteorological Institute and presented in Figure 7. Two separate ice regimes overlap with the seabird breeding colony off the NW coast. The ice regimes are reported using Egg codes [38]. To the south and nearest to shore (Egg Code 'G') is one-tenth total concentration of thick first-year ice. Adjacent and to the north (Egg Code 'C') is more severe ice, reported four-tenths old ice, two-tenths thick first-year, and one-tenth medium first-year ice.

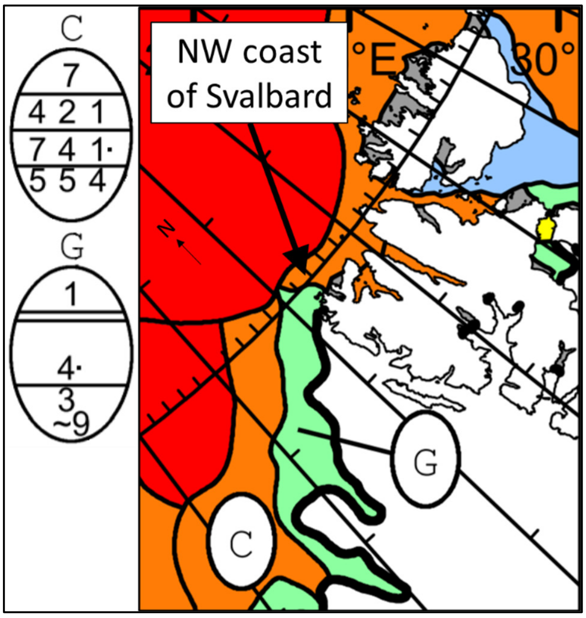

Figure 7. Ice conditions around the North West coast of Svalbard, Norway, 16 June 2019 (modified from Greenland Ice Chart, Danish Meteorological Institute, 16 June 2019 [39]).

The results of the risk assessment are presented in Table 15. Having been assigned a Polar class PC5, both vessels received standard RIOs of 27 in the ice regime 'G' (less severe ice conditions), and 2 in regime 'C' (more severe ice conditions). Based on the standard RIOs, the current POLARIS methodology would allow both vessels to undertake 'normal operations' in either ice regime.

Table 15. Risk assessment results for the benchmark case study.

Region	Vessel Type	PESCI	C	L	RIV_L	RIO (std)	RIO (mod)
Ice Regime G	oil tanker	1	C2	L1	−2	27	7
	cruise ship	3	C3	L1	−2	27	7
Ice Regime C	oil tanker	1	C2	L1	−2	2	−18
	cruise ship	3	C3	L1	−2	2	−18

Following the proposed risk assessment framework, both vessels were assessed as having a high operational exposure level, given the combinations of vessel type, ice conditions, and ecological sensitivity.

The cruise vessel had a high life-safety consequence value, which resulted in a high operational exposure level. In the less severe ice regime ('G'), the modified RIO was reduced to 2. This still allowed for 'normal operations' in this ice regime. In the more severe ice regime ('C'), the cruise vessel received a modified RIO of −18 ('operations subject to special consideration'). Given the life-safety consequence of cruise vessels operating around Svalbard, this ice regime should be avoided and the vessel should either choose an alternate route or delay operations in this region until ice conditions become less severe.

The oil tanker had a moderate life-safety consequence value and a high spill consequence value. Combined with the high ecological sensitivity of the region, it received a high operational exposure level. In the less severe ice regime ('G'), the oil tanker received a modified RIO of 2, allowing 'normal operations'. In the more severe ice regime ('C'), the oil tanker received a modified RIO of −18, requiring 'operations subject to special consideration'. Given the severity of the ice conditions, the high spill consequence, and the high ecological sensitivity related to the presence of the summer seabird breeding colony, the oil tanker should avoid operations in this ice regime and select an alternate route.

7. Discussion

It has been demonstrated that increased Arctic shipping activity poses potential risk to life and environmental safety. Nevertheless, it must be recognized that Arctic shipping brings positive economic impacts to Arctic communities and nations [8]. A balance must be sought between the mitigation of risk and the realization of benefits [9].

The proposed framework does not aim to apply restrictions that are so stringent that the benefits of Arctic shipping cannot be realized. Under normal circumstances when vessels are transiting areas that do not have protected status and have normal ecological conditions (e.g., no sensitivities) then no changes in operating limits are required. If an area has been identified as having higher sensitivities or the vessel is carrying a large amount of potential contaminant or a large POB, adjustments to operating limits or deviation of route may be required.

The current methodology for assessing the operational limits of a vessel in ice (i.e., POLARIS) accounts only for the likelihood of ice damage. The risk assessment framework proposed here links with the current POLARIS methodology and provides operational guidance considering life-safety, environmental, and socio-economic consequences that can result from ice damage. Such an approach promotes Arctic marine safety and the protection of the Arctic environment and its stakeholders.

The proposed framework provides a methodology to incorporate varying risk perspectives into an operational decision support tool. It provides an avenue to capture risk profiles for different vessels, input from local communities and stakeholders, input from marine environmental impact assessments, and input from other marine risk assessments.

There are existing geographic information system (GIS)-based technologies that could support the calculation and communication of this information on the bridge of a ship, such as the Canadian Arctic Shipping Risk Indexing System (CASRAS), an e-navigation tool combining information on historic ice conditions, marine protected areas, community services, and mariner knowledge [40].

Marine operations, particularly in the Polar regions, are complex socio-technical systems. Risk management should take a holistic, multidisciplined approach. To move towards a more holistic assessment of risk, stakeholder engagement is necessary to establish the range of risk perspectives from those affected by and involved in Arctic shipping. The severity of consequences resulting from an accident in the Arctic will depend, in part, on availability and capacity of emergency response resources. Methods for incorporating system thinking is an area requiring future research.

There are ice class design attributes that contribute to mitigating life-safety and environmental risk (e.g., double hull oil tankers) and not all ice damage results in EER or an oil spill. These factors require consideration in the determination of a vessel's operational exposure level.

This framework provides a potential avenue for linking diverse research across a range of fields including engineering, as well as biological, physical, and social sciences, as demonstrated in the benchmark case study. A multidisciplinary approach can help inform decision making at operational and regulatory levels.

It is important to note that the specific values and levels of granularity proposed here for the various risk indices are starting points for discussion, to be debated and subjected to robust calibration exercises. This will require input from ongoing scientific research across multiple disciplines.

Next steps include further investigation of the proposed life-safety and consequence categories and operational exposure levels, as well as calibration of RIV adjustment factors. The efficacy of operational risk mitigation strategies requires further research and validation. Empirical data should be collected to strengthen the knowledge underlying the calibration of the proposed framework. Implementation of this methodology in a GIS-based software would simplify application of this approach and could accelerate verification and calibration.

8. Conclusions

A new framework was presented which augments the current POLARIS methodology to model the potential consequences of ice-induced damage. The framework incorporates the magnitude of life-safety and environmental consequences to support operational decision making for ships operating in Polar regions. The proposed framework complements the existing POLARIS methodology and guides the formulation of RIVs for varying risks and consequences. The outcome is that vessels of a given ice class with higher potential life-safety, environmental, and socio-economic consequences should be operated more conservatively. Mitigating measures, such as reducing the number of people on board, selecting more environmentally friendly fuels, specifying a higher ice class during design, or incorporating operational measures (e.g., support icebreakers) can enhance the operability of the vessel.

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