MANAGING SAFE AND EFFICIENT ARCTIC SHIP OPERATIONS WITH RISK-BASED METHODS

by

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A Thesis submitted to the School of Graduate Studies

in partial fulfillment of the requirements for the degree of

Doctor of Philosophy

Faculty of Engineering and Applied Science

Memorial University of Newfoundland

1 June 2022

St. John's Newfoundland and Labrador

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ABSTRACT

A ship accident in the Arctic poses risks to the crew and passengers, the environment, Arctic communities, and other Arctic stakeholders. There are life-safety, ecological, and socio-economic consequences that require consideration in the operational risk management and regulation of Arctic ships. The objective of this thesis is to contribute to safe and efficient Arctic maritime operations. A scenario-based Arctic shipping operational risk management framework is proposed that integrates life-safety, ecological, and socio-economic consequences into the Polar Operational Limit Assessment Risk Indexing System (POLARIS) regulatory guideline. The proposed framework is then developed further. First, a scenario-based life-safety consequence model for Arctic ship evacuations is developed through elicitation of expert knowledge. Then a consequence aggregation method is developed to combine life-safety and environmental consequences of an Arctic ship accident. The development of regulations requires evaluations of the costs associated with regulatory implementation. Complementing the proposed augmentation of POLARIS, a general method to evaluate the operational implications incurred under maritime regulatory constraints is developed. The method combines a ship performance model, regulatory constraint models, and pathfinding and optimization algorithms. Results of the research show that the consequence severity of an Arctic ship accident depends on ship type and accident location. Worst-case scenario ship accidents are those involving cruise ships in regions associated with long response times and oil tankers in environmentally sensitive regions. With respect to the operational implications of regulatory constraints, POLARIS offers operational flexibility over the Arctic Ice Regime Shipping System

(AIRSS), but is associated with increased voyage time and fuel consumption. Implications for safe and efficient Arctic maritime operations can be drawn from the research. Vessels that pose higher life-safety and environmental consequences should be operated more conservatively. Continued enhancement of Arctic SAR services and advanced training for all Arctic seafarers will contribute to the mitigation of life-safety risk posed by Arctic shipping. Mitigating the risk associated with Arctic cruise operations is of near equal priority to that of Arctic tanker operations. POLARIS and AIRSS are decision-support tools that support safe Arctic navigation but should not replace competent Arctic crews.

ACKNOWLEDGEMENTS

Several individuals and organizations contributed to the completion of this PhD project and thesis and are acknowledged here.

The National Research Council of Canada – Ocean, Coastal and River Engineering Research Centre allowed me to take education leave to pursue the degree. Specific thanks to Dr. Dave Murrin, Dr. Martin Richard, and Matt Garvin.

The financial support of the Lloyd's Register Foundation and the National Research Council of Canada is gratefully acknowledged.

My supervisory committee consists of Drs. Brian Veitch, Rocky Taylor, Faisal Khan, and Doug Smith. They helped shape this research and guided me through the academic process. Special thanks to Dr. Brian Veitch for the frequent chats, mentorship, and teaching me how to research. Special thanks to Dr. Rocky Taylor for conceptualizing the topic of the first journal article.

Early in the PhD process I had the opportunity to visit several universities and pitch my thesis topic. The feedback was constructive and helped accelerate my timeline. Thank you to Drs. Pentti Kujala (Aalto University), Sören Ehlers (Technical University of Hamburg), Scott Mackinnon (Chalmers University), Steve Mallam (University of South Eastern Norway), and Inari Helle (University of Helsinki).

I was fortunate to develop many positive working relationships which resulted in collaborations and co-authorships. Thank you to Dr. Jennifer Smith, Trung Tien Tran, Dr. Inari Helle, and Dr. Tuuli Parviainen.

Writing and communication skills are critical in research. Special thanks to Dr. Jennifer Smith and Dr. Brian Veitch for the writing workshops. They were effective and timely.

Thanks to my family. To my parents for instilling their work ethic in me. To my wife, Emilie, for her support, encouragement, and patience. It has been a team effort. Thank you. To our daughter, Alberta, born in the fifth semester of the PhD. Perhaps you will read this someday. May it encourage you to pursue what you enjoy and not shy away from hard work.

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ACRONYMS AND ABBREVIATIONS

AIRSS	Arctic Ice Regime Shipping System
BRI	Biological Resource Indicator
CCG	Canadian Coast Guard
COE	Consequence of Exposure
EER	Escape, Evacuation, and Rescue
ESI	Environmental Sensitivity Index
FRAM	Functional Resonance Analysis Method
FSA	Formal Safety Assessment
HRI	Human-use Resource Indicator
ICEHR	Interdisciplinary Committee on Ethics in Human Research
IM	Ice Multiplier
IMO	International Maritime Organization
IN	Ice Numeral
ISO	International Organization for Standardization
LSA	Life Saving Appliances
MARPOL	International convention for the prevention of pollution from ships
MV	Motor Vessel
NSR	Northern Sea Route
NWP	Northwest Passage
PC	Polar Class
PESCI	Protection Status, Ecological Sensitivity, and Spill Consequence Index
POB	Persons On Board
Polar Code	International code for ships operating in polar waters
POLARIS	Polar Operational Limit Assessment Risk Indexing System
PPE	Personal Protective Equipment
PSC	Polar Ship Certificate

PSI	Physical Sensitivity Indicator
PWOM	Polar Water Operational Manual
RIO	Risk Index Outcome
RIV	Risk Index Value
SAR	Search and Rescue
SOLAS	International convention for the safety of life at sea
STCW	International convention on standards of training, certification and watchkeeping for seafarers
UNESCO	United Nations Education, Science, and Cultural Organization
ZDS	Zone Date System

1. INTRODUCTION

Arctic maritime operations are complex socio-technical systems. A ship accident in the Arctic poses a number of risks. Not only are the vessel, crew, and passengers exposed to risk, but the environment, Arctic communities, and other Arctic stakeholders may be negatively impacted. There are life-safety, ecological, and socio-economic consequences that require consideration in the risk management and regulation of Arctic ship operations.

The objective of this thesis is to contribute to the management of safe and efficient Arctic maritime operations. In the context of the thesis, safe operations mitigate risk associated with Arctic shipping, specifically life-safety, ecological, and socio-economic risks. Efficient operations optimize operational objectives of a voyage, specifically the reduction of voyage time, fuel consumption, and distance.

Contributions of the thesis and the coherence of the main chapters are introduced in Section 1.1. The theoretical framework for each main chapter is discussed in Section 1.2. Objectives and scopes of work are presented in Sections 1.3.

1.1. Contributions of thesis

There are two primary contributions of this research: a scenario-based Arctic shipping operational risk management framework that integrates consequences into conventional regulatory operational risk assessments, and a general method to evaluate the operational implications of Arctic maritime regulatory constraints.

The thesis is written in manuscript style, comprised of four journal articles presented in Chapters 2 to 5. Chapters 2 to 4 contribute to the Arctic shipping operational risk management framework. Chapter 5 presents the method to evaluate Arctic maritime regulatory constraints.

Chapter 2.	Browne, T., Taylor, R., Veitch, B., Kujala, P., Khan, F., Smith, D. 2020. A framework for integrating life-safety and environmental consequences into conventional Arctic shipping risk models. *Applied Science*, 10 (8), (2020) 2937.
Chapter 3.	Browne, T., Veitch, B., Taylor, R., Smith, J., Smith, D., Khan, F. 2021. Consequence modelling for Arctic ship evacuations using expert knowledge, *Marine Policy*, 130 (2021), 104582.
Chapter 4.	Browne, T., Taylor, R., Veitch, B., Helle, I., Parviainen, T., Khan, F., Smith, D. 2022. A consequence aggregation method for Arctic ship accidents. Submitted (January 2022).
Chapter 5.	Browne, T., Tran, T., Veitch, B., Smith, D., Khan, F., Taylor, R. 2022. A method for evaluating operational implications of regulatory constraints on Arctic shipping. *Marine Policy*, 135 (2022), 104839.

Chapter 2 proposes an Arctic shipping operational risk management framework which considers potential life-safety consequences of an Arctic ship evacuation and environmental consequences of an Arctic marine oil spill. The proposed framework is intentionally amenable to being adopted and adapted to existing maritime regulations. Through an augmentation of the Polar Operational Limit Assessment Risk Indexing System (POLARIS) regulatory guideline, the framework provides a mechanism to assign operating limits to ships in ice based on the potential consequence severity posed by an ice damage event.

Contributing to the development of the Arctic shipping operational risk management framework, a scenario-based life-safety consequence model for Arctic ship evacuations is established in Chapter 3, and a method to aggregate life-safety and environmental consequences of Arctic ship accidents is developed in Chapter 4.

The development of regulations should be supported by evaluations of the costs associated with their implementation. To complement the proposed augmentation of an existing Arctic maritime regulation, a general method to evaluate the operational implications incurred under different Arctic maritime regulatory constraints is developed in Chapter 5. The method employs pathfinding algorithms to identify optimal routes under different regulatory constraints, and a ship performance model to measure operational implications.

The contributions and coherence of the main chapters of the thesis are depicted in Figure 1.1.

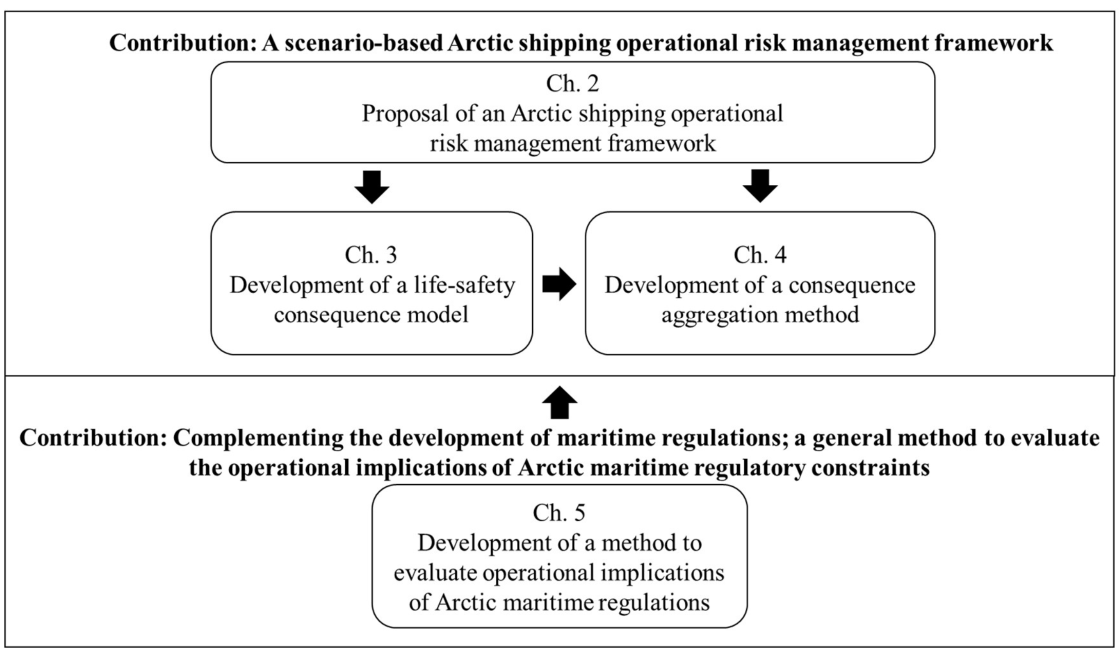

Figure 1.1. Coherence of thesis chapters.

The thesis is concluded in Chapter 6 with a summary of main findings of the research, implications for safe and efficient Arctic maritime operations, and a discussion of limitations of the research and areas for future work

1.2. Theoretical framework

The theoretical framework underlying the main chapters of the thesis are discussed in this section.

1.2.1. Integrating consequences into operational risk assessments

Arctic maritime operations are complex socio-technical systems [1-3] exposed to a number of unique risks [4-6]. A ship accident in the Artic poses potential consequences to crew and passengers, the environment, Arctic communities, and other Arctic stakeholders [7].

Safe Arctic ship operations are supported by risk-based maritime regulations [8-10]. Recognizing the unique risks associated with Arctic shipping, the International Maritime Organization (IMO) adopted the International Code for Ships Operating in Polar Waters (Polar Code) [6], including the POLARIS regulatory guideline as a risk-based decision support tool for assessing safe operating limits in sea ice [11].

While POLARIS has been shown to reflect the risk of structural damage to a vessel in ice [12], POLARIS does not account for the potential consequences resulting from an ice damage event, e.g. life-safety consequences of a ship evacuation, and ecological and socio-economic consequences of an oil spill.

Ships that pose greater potential consequences should be operated more conservatively. Integrating consequences into existing Arctic shipping operational risk assessments will contribute to more holistic risk management of Arctic ship operations and enhance the safety of crew and passengers and protection of the Arctic environment and its stakeholders.

1.2.2. Life-safety consequence of Arctic ship evacuations

The proposed Arctic shipping operational risk management framework considers life-safety consequences of a ship evacuation. Life-safety risk is an area of risk concerning the level of harm to humans, considering illness, injury, and death [13]. The IMO Formal Safety Assessment (FSA) guidelines recommend incorporating life-safety consequence in the assessment of Arctic maritime industry risk.

Evaluating the life-safety consequence severity of an Arctic ship evacuation is challenging. A lack of accident data for Arctic regions prevents the use of conventional statistical approaches to assess life-safety consequence [4].

A number of studies have analyzed Arctic ship accident data [4,7-9,14-19]. Studies have also investigated factors that influence the potential for loss of life during Arctic ship evacuations, including search and rescue (SAR) capabilities [4,20,21], SAR response times [22], and the performance of life-savings appliances (LSA) [23].

While these studies provide insight into accident frequencies and risk factors, the data is insufficient to support the evaluation of life-safety consequence. The absence of a life-safety consequence model for Arctic ship evacuations represents a gap in the current body knowledge.

1.2.3. Aggregating consequences of Arctic ship accidents

In the context of the thesis, the proposed Arctic shipping operational risk management framework combines life-safety, ecological, and socio-economic consequences to determine operating limits for ships in ice. A method to aggregate individual consequences and estimate total consequence severity is necessary.

A system exposed to multiple risks requires decision-makers to consider total exposure to loss. Risk aggregation is the process of combing multiple individual risks to establish a better understanding of the total risk on a system. Evaluating total risk provides context for individual risks and allows for comparison of risk scenarios and prioritization of risk management efforts [24,25].

A risk is often characterized by the consequence and associated uncertainty of an activity. Risk characterization aggregation refers to the aggregation of individual measures of consequence of multiple risks, while the uncertainty associated with the realization of the multiple consequences is expressed as a single measure [24].

On the premise that the operational risk management of Arctic shipping should consider the multiple consequences posed by a ship accident scenario, there is a need to establish a consequence aggregation method for Arctic ship accidents. Evaluating total consequence severity of Arctic ship accident scenarios will contribute to the prioritization and assignment of risk-based operating limits.

1.2.4. Operational implications of Arctic maritime regulations

A regulation shapes behaviours to address a problem of concern. In addition to addressing a problem of concern, there are costs associated with regulatory implementation. Regulations should be evaluated on their efficacy in addressing the problem and the costs associated with implementing the regulation [26,27].

Maritime regulations have implications on the operational objectives of a ship [28]. It is argued that the regulatory cost assessment in the IMO FSA guidelines, which are intended for use in the IMO rule-making process, does not consider the costs incurred by those responsible for regulatory implementation [29]. The effective development of maritime regulations necessitates evidence-based and data-driven evaluations of the effects of regulatory constraints on ship operations.

Within the Canadian Arctic, three regulations promote safe ship operations in ice through the assignment of operational constraints: POLARIS, the Arctic Ice Regime Shipping System (AIRSS), and the Zone Date System (ZDS) [30]. Studies have investigated POLARIS, AIRSS, and the ZDS, focusing on regulatory efficacy, risk mitigation, and regulatory limitations [8-10,12,31,32]. There exists a gap in the research literature regarding methods to evaluate the operational implications of Arctic maritime regulations.

To complement the proposed augmentation of POLARIS (Chapter 2), there is a need for evidence-based and data-driven evaluations of the operational implications incurred under Arctic maritime regulations.

1.3. Research objectives and scopes of work

The objectives and scopes of work of this thesis are guided by a number of research questions, and summarized in Table 1.1. The research objectives and scopes of work are discussed in the context of the theoretical framework and contributions.

1.3.1. Integrating consequences into Arctic shipping operational risk assessments

The premise of Chapter 2 is that if two ships with the same ice class operate in the same ice conditions, the vessel posing higher potential consequences for life and/or environmental safety should be operated more conservatively. While two operating scenarios may pose the same risk of structural damage, when consequence severities are considered, the overall risk may be higher or lower and this should be reflected in the required operating limits.

The POLARIS regulatory guideline assigns operating limits to ships in ice. Based on vessel ice class and prevailing ice conditions, Risk Index Values (RIVs) are assigned and a Risk Index Outcome (RIO) value is calculated. Operating limits are assigned based on the calculated RIO [11]. POLARIS has been shown to reflect the likelihood of structural damage due to ship-ice interaction [12], but does not consider the potential consequences of a ship-ice damage event.

The objective of this research is to investigate ways in which life-safety and environmental safety considerations may be applied to support operational decision-making for ships navigating in polar regions.

The International Organization for Standardization (ISO) 19906 standard provides an approach to consider life-safety, ecological, and economic consequences in the assignment of risk-based design criteria for Arctic offshore structures [33].

An Arctic shipping operational risk management framework is proposed in which an exposure adjustment term that reflects potential consequence severity is added to the POLARIS methodology. Following a similar approach as ISO 19906, life-safety, ecological, and socio-economic consequence categories inform the assessment of a vessel's exposure level. The exposure level corresponds to an RIV adjustment factor. The proposed framework guides the formulation of a modified RIO corresponding to the magnitude of life-safety, ecological, and socio-economic risks and consequences.

1.3.2. Life-safety consequence model for Arctic ship evacuations

Chapter 3 is founded on the premise that there does not exist a life-safety consequence model for Arctic shipping. The objectives of the research are to 1) investigate the factors that influence the potential for loss of life, and 2) evaluate the consequence severity resulting from ship evacuations in Arctic waters.

Recognizing the lack of accident data for Arctic shipping, the study employs expert knowledge elicitation. Arctic shipping experts in the fields of seafaring, policy and regulation, academia and research, and ship design are recruited.

A two-phased mixed methods design is used to elicit expert knowledge. Phase 1 is qualitative with semi-structured interviews conducted to identify the factors that influence the potential for loss of life during a ship evacuation in Arctic waters. Phase 2 is quantitative and subjective. A survey is developed based on the results of the interviews. Experts rate the level of life-safety consequence severity posed by Arctic ship evacuation scenarios. The result of the study is a scenario-based life-safety consequence model for Arctic ship evacuations.

While the study contributes to the development of the proposed Arctic shipping operational risk assessment framework (Chapter 2), the consequence model is a contribution to the body of knowledge independent of the framework. Modelling life-safety consequence contributes to more holistic risk-based decision-making for Arctic maritime policy, regulation, and operations.

1.3.3. Aggregating consequences of Arctic ship accidents

There are two premises to Chapter 4: 1) Arctic shipping operational risk management should consider the multiple consequences posed by a ship accident, and 2) evaluating total risk allows for the comparison of risk scenarios and prioritization of risk management efforts. The objective of this research is to establish a general method to aggregate consequences posed by Arctic ship accident scenarios.

A quantitative aggregation method combines the life-safety consequence model for Arctic ship evacuations (Chapter 3) with an existing environmental consequence model for Arctic marine oil spills [34]. The environmental consequence model reflects ecological and socio-economic impacts. Consequence aggregation is achieved through monetization and summing of individual consequence costs. The aggregated consequence severity for an accident scenario is estimated as the total consequence cost.

A framework to qualitatively rate total consequence severity is proposed, using predefined matrices to evaluate and aggregate qualitative consequence categories based on ship type and geographic region. The qualitative categories of the framework are defined based on the quantitative consequence aggregation method.

While the study contributes to the development of the proposed Arctic shipping operational risk assessment framework (Chapter 2), the consequence aggregation method is a contribution to the body of knowledge independent of the framework. The method provides a tool to integrate multidisciplinary knowledge for the assessment, management, and communication of Arctic shipping risks.

1.3.4. Evaluating operational implications of Arctic maritime regulations

The premise of Chapter 5 is that there exists a gap in the research literature regarding methods to evaluate the operational implications of Arctic maritime regulations. The research objective is to establish a general method to evaluate the operational implications incurred under maritime regulatory constraints.

The method combines a ship performance model, regulatory constraint models, and multi-criteria pathfinding and optimization algorithms. The ship performance model provides estimates of operational implications, measured as voyage time, fuel consumption, and distance. A multi-criteria cost function allows for prioritization of operational objectives.

The method is applied to the case of Arctic shipping. Four approaches for assigning structural safety constraints for ships in ice are modelled: the AIRSS and POLARIS regulatory guidelines, speed limits established through a first-principles ship-ice interaction model [35], and navigation in the absence of structural safety constraints. Optimal routes and speeds for a Polar Class 5 (PC5) vessel transiting the Northwest Passage are identified. Optimized routes and speeds are validated against the expert opinions of Arctic ship captains.

The method provides policy-makers, classification societies, and other Artic shipping stakeholders with a tool to evaluate the operational implications associated with maritime regulations and to assess economic implementation strategies.

Table 1.1. Summary of research questions, objectives, and scopes of work.

Chapter	Research questions	Objectives	Scope of work
Ch. 2. A framework for integrating life-safety and environmental consequences into conventional Arctic shipping risk models	• What is the current approach to operational decision-making and risk management of ice-class vessels in Canada? • What does the current state of practice account for in terms of management of life-safety and environmental risks?	Investigate how life-safety and environmental safety considerations can support the operational decision-making for ships in polar regions.	• Assess the Polar Code and POLARIS for treatment of life-safety and environmental risk. • Identify the risk definition adopted by POLARIS. • Integrate life-safety, ecological, and socio-economic consequence categories and an exposure adjustment term into POLARIS for the assignment of risk-based operating criteria. • Demonstrate application of the proposed operational risk management framework with a case study.
Ch. 3. Consequence modelling for Arctic ship evacuations using expert knowledge	• What factors influence the potential for loss of life resulting from a ship evacuation in the Arctic? • What is the severity level posed by different ship types and evacuation scenarios?	Investigate factors that influence the potential for loss of life, and the evaluate consequence severity resulting from ship evacuations in Arctic waters.	• Elicit expert knowledge through a two a two-phased mixed methods design. • Semi-structured interviews: identify factors that influence the potential for loss of life. • Survey: rate the level of life-safety consequence severity posed by Arctic ship evacuation scenarios. • Validate results against benchmark case studies.
Ch. 4. A consequence aggregation method for Arctic ship accidents	• How can multiple consequences (life-safety, ecological, socio-economic) posed by Arctic ship accidents be assessed? • How can these multiple consequences be aggregated? • What mechanism can be used to evaluate total consequence to support Arctic ship operational decision-making?	Establish a general method to aggregate consequences posed by Arctic ship accident scenarios.	• Combine the life-safety consequence model from Ch. 2 with ecological and socio-economic models adopted from the literature. • Establish a common unit for consequence severity (dollar value). • Estimate total consequence severity as a total consequence cost. • Establish a qualitative framework to rate total consequence severity, providing a mechanism to support operational decision-making.
Ch. 5. A method for evaluating the operational implications of regulatory constraints on Arctic shipping	• What approaches are currently used to assess the potential impacts of proposed changes to maritime regulations? • What impact do regulatory constraints have on Arctic ship operations? • How do existing Arctic shipping regulatory constraints (AIRSS and POLARIS) compare to safe speeds based on first-principles ship-ice interaction modelling?	Establish a general method to evaluate the operational implications incurred under maritime regulations.	• Investigate the use of pathfinding as a means to evaluate the operational implications incurred under operational constraints. • Combine a ship performance model, regulatory constraint models, and multi-criteria pathfinding and optimization algorithms to identify optimized routes. • Evaluate operational implications, measured as voyage time, fuel consumption, and distance, using the ship performance model. • Apply the method for a Polar Class (PC) 5 vessel navigating the Northwest Passage under AIRSS and POLARIS guidelines. • Validate optimized routes and speeds against expert opinion.

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2. A FRAMEWORK FOR INTEGRATING LIFE-SAFETY AND ENVIRONMENTAL CONSEQUENCES INTO CONVENTIONAL ARCTIC SHIPPING RISK MODELS

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2.1. Co-authorship statement

T. Browne: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Writing –review & editing. **R. Taylor**: Conceptualization, Methodology, Writing – review and editing, Supervision. **B. Veitch**: Writing – review & editing, Supervision, Project administration, Funding acquisition. **P. Kujala**: Writing – review & editing, Funding acquisition. **F. Khan**: Writing – review & editing, Supervision, Funding acquisition. **D. Smith**: Writing – review & editing, Supervision.

2.2. 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.

2.3. 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 2.4 compares the design code philosophies of the Polar Code and ISO 19906. Section 2.5 reviews the challenges associated with evaluating life-safety and environmental consequences of Arctic shipping. Section 2.6 introduces the proposed life-safety and environmental consequence framework. Section 2.7 provides scenarios to illustrate the flexibility of the methodology in accounting for varied risk profiles and different vessel types and cargos. In Section 2.8, the framework is applied to a benchmark case study incorporating data from published Arctic marine shipping assessments. Section 2.9 discusses the merits of the proposed framework and areas for future work. Section 2.10 is the conclusion.

2.4. Background

2.4.1. 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.

2.4.2. 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.

2.4.3. 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 Eq. 2.1:

$$RIO = (C1 \times RIV_1) + (C2 \times RIV_2) + \cdots + (C_n \times RIV_n) \tag{2.1}$$

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' (RIO ≥ 0), 'elevated operational risk' ($-10 \leq$ RIO ≤ 0), or 'operation subject to special consideration' (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.

2.4.4. 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 2.1 is used to determine the exposure level as a function of life-safety categories and consequence categories [11].

Table 2.1. 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.

2.4.5. 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).

2.5. Arctic shipping risk

2.5.1. 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.

2.5.2. 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 2.1 summarizes the range of factors and foundational issues that should to be considered in the evaluation of consequences of Arctic shipping.

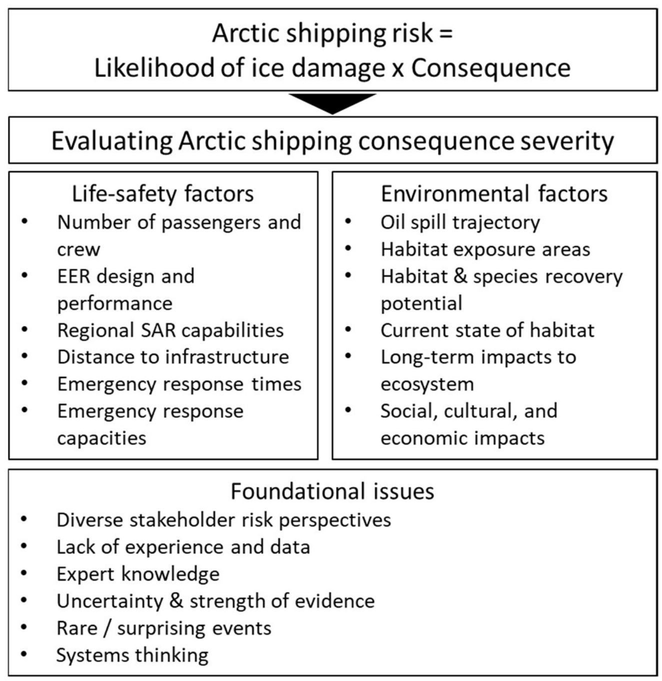

Figure 2.1. The factors and foundational issues that influence the evaluation of Arctic shipping consequences.

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.

2.6. 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 2.2 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.

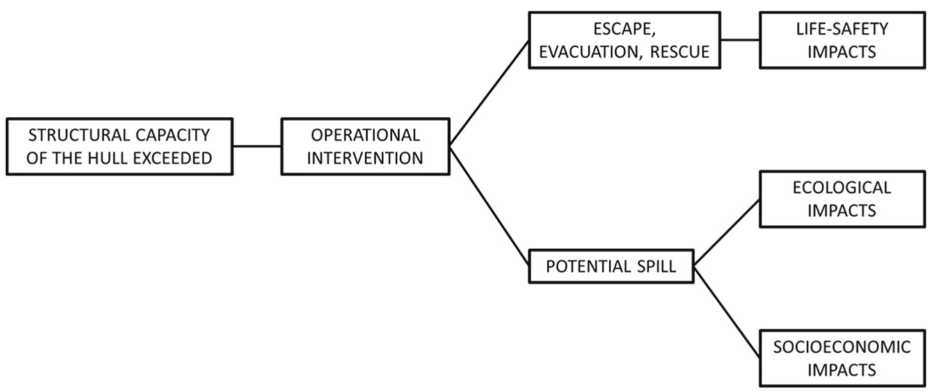

Figure 2.2. The chain of consequences following ice damage to a vessel considering life and environmental safety.

2.6.1. 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.

2.6.2. 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 2.2.

Table 2.2. 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 2.2 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.

2.6.3. Environmental and 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.

2.6.3.1. 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 2.3).

Table 2.3. 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 2.3 illustrates how geographically referenced maps can be used to communicate regions with socio-economic protection status.

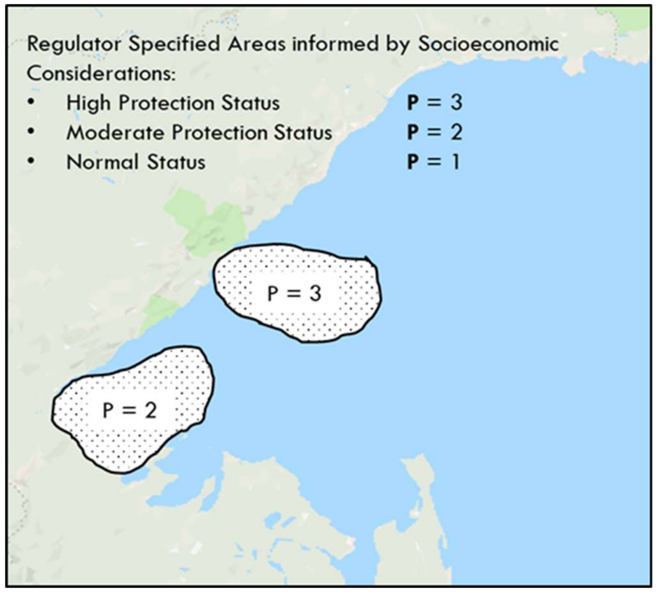

Figure 2.3. Examples of geographic regions defined as requiring socio-economic protection status.

2.6.3.2. 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 2.4). Policy information can be communicated in a similar fashion as proposed for regions requiring socio-economic protection status (Figure 2.3), including any special operating requirement for vessels in these regions.

Table 2.4. Ecological sensitivity categories.

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

2.6.3.3. 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 2.5. 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 2.5. 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.

2.6.3.4. 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 2.6 a,b,c, which corresponds to socio-economic protection category values (P) of 1, 2, and 3, respectively.

Table 2.6. PESCI values.

Arctic Ice Regime Shipping **System**	
Biological Resource Indicator	
Canadian Coast Guard	
Consequence of Exposure	
Escape, Evacuation, and Rescue	

The PESCI value corresponds to an overall consequence category of high (C1), moderate (C2), or normal (C3), in accordance with Table 2.7.

Table 2.7. Consequence categories.

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

2.6.4. 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 2.8. 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 2.8. 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		

2.6.5. 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 2.9.

Table 2.9. 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 Eq. 2.2.

$$RIO_{modified} = C_1 \times (RIV_1 + RIV_L) + C_2 \times (RIV_2 + RIV_L) + \cdots + C_n \times (RIV_n + RIV_L) \qquad (2.1)$$

where $C_1 \ldots C_n$ = concentration (in tenths) of each ice type within the ice regime, $RIV_1 \ldots RIV_n$ = 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 2.4.

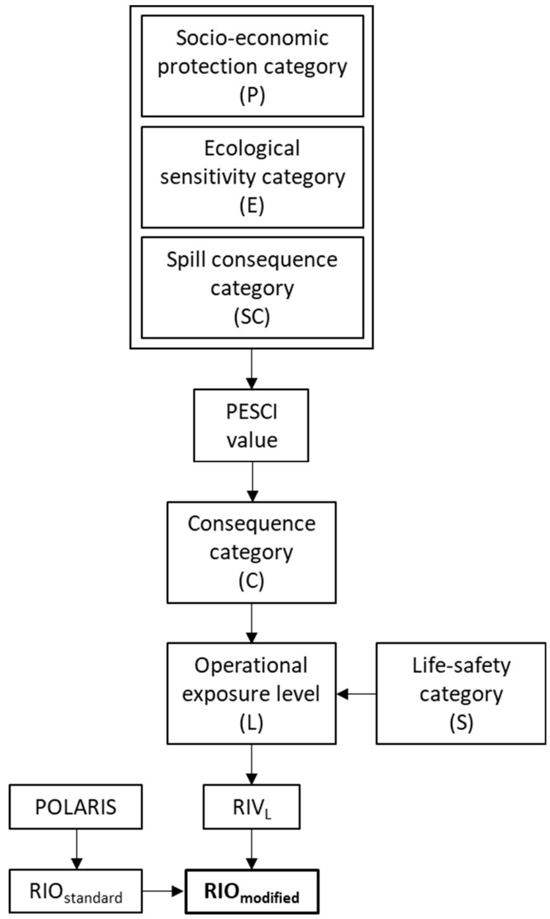

Figure 2.4. Risk assessment framework process.

2.7. 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 2.5).

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.

2.7.1. Route identification

The planned voyage departed from a northern port and arrived at a port in the south, as depicted in Figure 2.5. Two different ice regimes were present. The ice types and associated concentrations for each ice regime are presented in Table 2.10.

Table 2.10. 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).

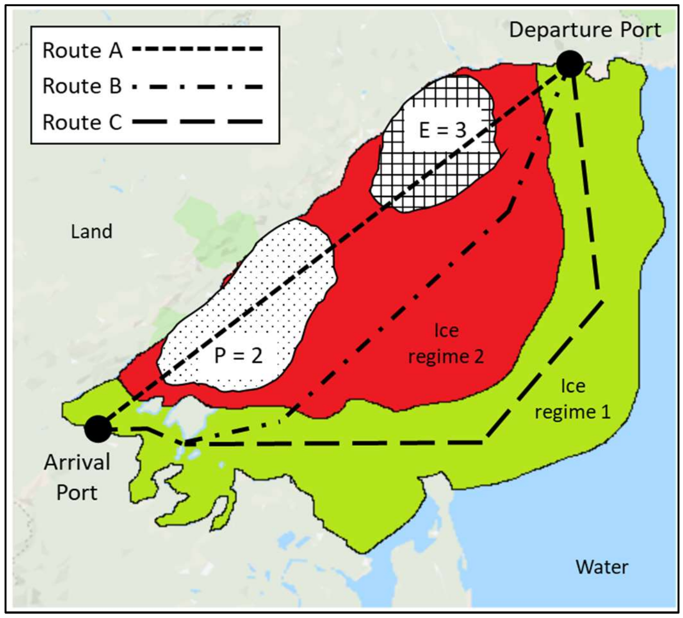

Figure 2.5. Waterway and routes for illustrative example.

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.

2.7.2. 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 2.11.

Table 2.11. 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.

2.7.3. 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 2.12.

Table 2.12. 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.

2.7.3.1. 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.

2.7.3.2. 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.

2.7.3.3. 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.

2.7.3.4. 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.

2.7.3.5. *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.

2.7.3.6. *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 2.13 below.

Table 2.13. 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.

2.8. 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 m3 of crude oil after running aground off the coast of Alaska in 1989 [36]. The Motor Vessel (MV) Explorer cruise ship had approximately 210 m3 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 2.14. For the purpose of this study, both vessels were assumed to have a Polar Class of PC5.

Table 2.14. 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 2.6). This region is evaluated as having a high ecological sensitivity to oil spills (E = 3).

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.

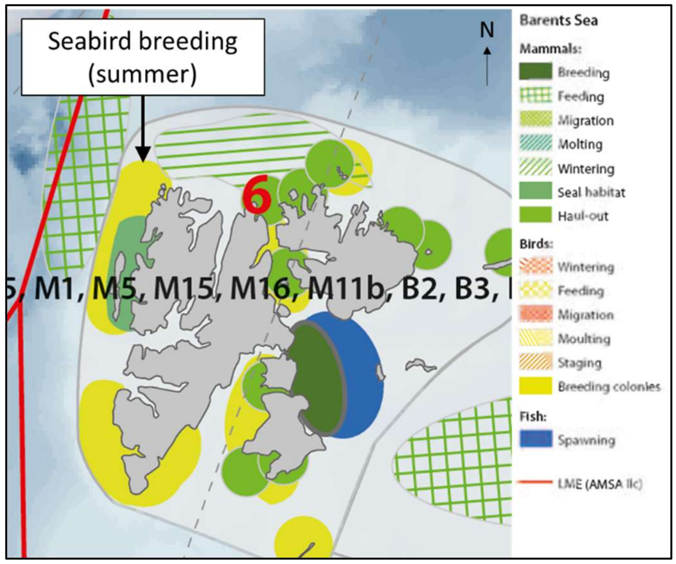

Figure 2.6. Areas of heightened ecological significance around Svalbard, Norway, (modified from Figure A.6 [24]).

The ice conditions on 16 June 2019 were used for the case study, as reported by the Danish Meteorological Institute and presented in Figure 2.7. 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.

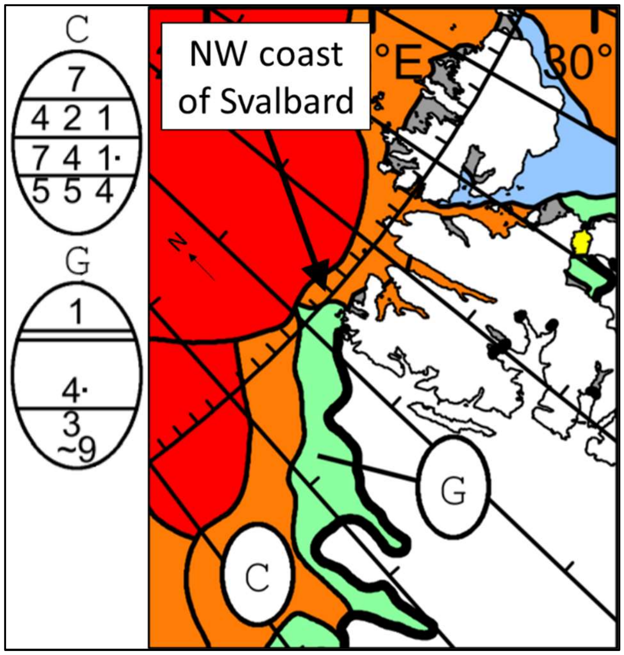

Figure 2.7. Ice conditions around the North West coast of Svalbard, Norway, 16 June 2019 (modified from Greenland Ice Chart, Danish Meteorological Institute, 16 June 2019 [39]).

The results of the risk assessment are presented in Table 2.15. 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 2.15. 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.

2.9. 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, multidiscipline 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.

2.10. Conclusion

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.

2.11. Acknowledgements

The financial support of the Lloyd's Register Foundation is acknowledged with gratitude. Lloyd's Register Foundation helps to protect life and property by supporting engineering-related education, public engagement, and the application of research.

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3. CONSEQUENCE MODELLING FOR ARCTIC SHIP EVACUATIONS USING EXPERT KNOWLEDGE

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3.1. Co-authorship statement

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3.2. Abstract

Risk-based decision-making is central to the development of Arctic shipping policy and regulation. Policy-makers within the International Maritime Organization rely on the Formal Safety Assessment (FSA) method-ology to evaluate proposed regulatory changes and Arctic ship operators rely on it to establish operating limits and procedures. The FSA recommends incorporating life-safety consequence in the assessment of maritime industry risk. This paper presents an expert-based assessment of the factors that influence the potential for loss of life during an Arctic ship evacuation and quantified consequence severities for a range of evacuation scenarios. A two-phased mixed methods design is used to elicit expert knowledge. Sixteen experts in the fields of Arctic seafaring, policy and regulation, academia and research, and ship design participated in the study. Semi-structured interviews elicited perspectives on the factors that influence the expected number of fatalities resulting from an evacuation in Arctic waters. Surveys were administered in which evacuation scenarios were rated for the level of life-safety consequence severity they pose. This study provides a scenario-based life-safety consequence model for Arctic ship evacuations. Results show evacuation of passenger vessels poses the highest consequence severity of evaluated ship types. Response time and the time available to evacuate have the greatest levels of influence on consequence severity. Implications for Arctic marine policy include the need for enhanced competency and training for Arctic ship crews and SAR services, continued research and development of Arctic life-saving appliances to satisfy Polar Code functional requirements, heightened regulatory oversight of Arctic cruise operations, and consideration of inclusion of fishing vessels under the Polar Code. Application of the results to the FSA methodology is discussed.

3.3. Introduction

The evacuation of a ship in Arctic waters exposes crew and passengers to a number of unique risks and an increased potential for severe consequences. Cold temperatures, extended periods of darkness, limited regional search and rescue capabilities, long response times, and inadequate emergency response capacities contribute to the increased potential for loss of life [1,2]. The evacuation of a cruise ship in the Arctic poses a particularly high risk for loss of life due to the inability of emergency responders to effectively rescue the large number of persons (crew and passengers) onboard (POB) [3].

Mitigating life-safety risk requires an understanding of the factors that influence consequence severity. Evaluating life-safety consequence severity for Arctic shipping is challenging. A lack of accident data for Arctic regions prevents the use of conventional statistical approaches to assessing life-safety risk [1]. The accident data that does exist often has insufficient detail on the circumstances surrounding the accidents, and historical data may not be relevant for new ship technologies [4].

Existing studies have modelled life-safety consequence for non-Arctic regions using global accident statistics and expert judgement [5-7]. These models do not capture the increased potential for loss of life associated with an evacuation in Arctic waters.

The lack of sufficient accident data and life-safety consequence models for Arctic regions represents a research gap in the current literature [1,4,8]. There is a need to evaluate the increased life-safety consequence severity posed by Arctic ship evacuations.

The focus of this study is to investigate the factors that influence the potential for loss of life of crew and passengers and evaluate the consequence severity level resulting from ship evacuations in Arctic waters. Evacuation scenario factors include different ship types and numbers of POB, and combinations of season, ice conditions, wind and sea state, time available to evacuate, and response time. Modelling life-safety consequence severity will contribute to more holistic risk-based decision-making for Arctic maritime policy, regulation, and operations.

A two-phased mixed methods design is used to elicit expert knowledge. Phase 1 is qualitative with semi-structured interviews conducted to identify the factors that influence the potential for loss of life during a ship evacuation in Arctic waters. Phase 2 is quantitative and subjective. A survey is developed based on the results of the interviews. Experts rate the level of life-safety consequence severity posed by Arctic ship evacuation scenarios.

The result of the study is an expert-based life-safety consequence model for Arctic ship evacuations. Evaluating causal factors or the likelihood of an evacuation is outside the scope of the current study.

3.3.1. Defining life-safety consequence severity

The International Maritime Organization's (IMO) revised guidelines for Formal Safety Assessment (FSA) [9] provide policy-makers within IMO with a methodology to assess maritime industry risks and evaluate the benefits and costs of proposed regulatory changes. There are three primary consequence categories recommended for consideration in the FSA methodology: life-safety consequences, environmental impacts, and property damage.

Life-safety risk is defined as an area of risk concerning the level of harm to humans. It considers illness, injury, and death but is typically narrowed to loss of life. Equivalence relations attempt to link numbers and severities of injuries to numbers of fatalities. For example, ten minor injuries equate to one severe injury, and ten severe injuries equate to one fatality.

A four-point severity index scale is common, with a fifth point added when assessing vessels that pose elevated life-safety risk (e.g. passenger vessels). Severity indices correspond to orders of magnitude of equivalent fatalities.

Table 3.1 presents a five-point life-safety consequence severity index following the IMO FSA guidelines. Severity levels range from minor to disastrous and equivalent fatality values are defined for each.

Table 3.1. Life-safety consequence severity definitions (modified from the FSA guidelines [9]).

Severity index	Severity	Effects on human safety	Equivalent fatalities
1	Minor	Single or minor injuries	0.01
2	Severe	Multiple or severe injuries	0.1
3	Significant	Single fatality or multiple severe injuries	1
4	Catastrophic	Multiple fatalities	10
5	Disastrous	Large number of fatalities	100

Life-safety risk may consider individual risk and societal risk. Individual risk is the risk of injury or death to a specific individual at a specific location for a given accident scenario. Societal risk is the average risk of injury or death experienced by a large number of people. Societal risk is not specific to an individual or location.

For the current study, the life-safety risk associated with the evacuation of crew and passengers is treated as a societal risk. Life-safety consequence severity is measured as the expected number of fatalities resulting from the evacuation.

3.3.2. Polar Code and mitigating life-safety risk

The following section introduces provisions of the IMO Polar Code [10] that address life-safety risk associated with evacuation. The efficacy of the Polar Code in mitigating life-safety risk is discussed.

The IMO International Convention for the Safety of Life at Sea (SOLAS) [11] is the primary regulatory instrument governing maritime life-safety. Recognizing that the demands and risks of navigating in polar waters is not sufficiently covered by SOLAS and other existing regulatory instruments, the IMO Polar Code [10] was adopted as an amendment to SOLAS and the International Convention for the Prevention of Pollution from Ships (MARPOL) [12]. The Polar Code provides goal- and risk-based requirements for design and construction, equipment, life-saving appliances, communication, voyage planning and safe navigation, crew training, and environmental protection in polar waters.

The Polar Code requires vessels to complete risk-based operational assessments to establish operating limits and procedures for both normal and emergency operations. Risk assessments follow the IMO FSA guidelines, focusing on safety of ships and protection of life and environment. Vessel-specific procedures and operating limits are documented in the Polar Water Operational Manual (PWOM). Vessels are required to carry a Polar Ship Certificate (PSC) that demonstrates the vessel has been surveyed in accordance with requirements of the Polar Code and assigned an ice class sufficient for its assessed operating limits [8,10].

Provisions of the Polar Code that mitigate life-safety risk associated with an evacuation include requirements for life-saving appliances (LSA) and arrangements, communication, voyage planning, and manning and training.

Vessels are required to carry LSAs that provide means for safe evacuation in all anticipated metocean and sea ice conditions. Crews must be competent in the use of LSAs for all conditions. Immersions suits and survival craft must provide adequate thermal protection to prevent hypothermia for the maximum expected time to rescue, which is no less than five days. This requires consideration of wind, cold, and potential immersion in polar waters.

A ship must be able to maintain effective communication ship-to-ship and ship-to-shore along the entire planned route. Should an evacuation occur, survival craft must be able to maintain on-scene communication with search and rescue (SAR) assets for the minimum five days. Ship and survival craft communications must remain functional, taking into account the limitations of communication systems at high latitudes.

Voyage planning must account for expected ice conditions, places of refuge, and operations in regions remote from SAR infrastructure. Manning and training provisions require masters and navigational watch officers of Arctic ships to receive specific training for safe operations in ice covered waters.

Fedi et al. [8] investigated the efficacy of the Polar Code as a risk assessment and mitigation tool. Benefits of the Polar Code include the identification of main risks, addressing voyage planning requirements, and the addition of provisions for navigation aids, crew fatigue, and Arctic LSAs. The operational assessment required by the Polar Code provides a structured framework for Arctic shipping risk management. It is argued that the proceduralized approach to risk management may promote an increase in Arctic ship traffic which, overtime, will address the current lack of ship accident data for Arctic regions.

Several shortcomings of the Polar Code were highlighted [8]. The Polar Code excludes fishing vessels and pleasure craft, and insufficiently covers low ice class vessels and operations in light ice conditions. Crew experience is not considered and advanced training for all Arctic crews is not required. The lack of SAR infrastructure in Arctic regions is not addressed.

The Polar Operational Limit Assessment Risk Indexing System (POLARIS) methodology [13] was introduced as part of the Polar Code [10]. POLARIS is a risk-based methodology that assigns operational restrictions for vessels navigating in ice, considering a vessels assigned ice class and the ice regime in which it intends to operate. POLARIS supports route planning, establishing vessel operating limits, and monitoring performance in ice [14]. POLARIS is considered an effective decision support tool not only for the master, crew, and ship owners, but also for classification societies, underwriters, and coastal state governance [15].

POLARIS models risk as the likelihood of a vessel to incur damage based on the structural capacities of the vessel and the ice regime. POLARIS does not consider any potential consequences that could result from a damage event. Browne et al. [16] argue the evaluation of Arctic shipping operational risk in the POLARIS methodology should be expanded beyond the risk of structural damage. A framework was proposed to incorporate a life-safety consequence category, as well as environmental and socio-economic consequence categories, in the POLARIS methodology. This more holistic risk perspective guides operational decision-making such that vessels having higher potential life-safety consequences are operated more conservatively. Similarly, Fedi et al. [15] argue that

POLARIS is not a self-sufficient risk framework, as it considers only ice class and ice conditions. Additional data and operational risk management tools are necessary for sound risk-based decision-making for Arctic operations.

3.3.3. Modelling life-safety risk and consequence severity

The following section discusses several approaches for modelling life-safety risk and consequence severity in the maritime industry. These include Arctic and non-Arctic applications, the use of historical data and expert opinion, and studies of factors that influence consequence severity. The role of Arctic SAR services is introduced and associated studies are discussed.

3.3.3.1. Non-Arctic studies

The SAFEDOR project investigated risk-based design solutions for different ship types following the FSA methodology. SAFEDOR focused on conventional, non-Arctic maritime operations. The results of the project were adopted by the IMO as FSA submissions [5-7].

The risk for different accident scenarios (e.g. contact, collision, grounding, fire) was modelled using event trees. Probabilities of occurrence for the event trees were modelled using historical accident data. End-scenarios of the event trees represent ship survivability outcomes with associated life-safety consequence severities. Severities were measured as expected numbers of fatalities, estimated as a percentage of the total POB (i.e. a societal risk).

Cargo vessels were modelled with a single ship survivability end-scenario and fatality estimates were calculated from historical accident data. Cruise and RoPax vessels were modelled with three ship survivability scenarios: vessel remains afloat, slow sinking, and rapid capsize. The expected number of fatalities were modelled based on expert opinion.

The ship survivability scenarios for the cruise and RoPax vessels include two sinking scenarios. The sinking scenarios produce significantly different fatality levels. The expected number of fatalities for a slow sinking scenario was modelled as 5% of the total POB. The expected number of fatalities for a rapid capsize was modelled as a distribution. Fatalities were estimated at 40%, 80%, and 100% of the total POB in 20%, 60%, and 20% of rapid capsizes cases, respectively.

3.3.3.2. Arctic studies

This section first discusses Arctic accident datasets. Following this, studies on Arctic SAR, response times, and LSAs are discussed in relation to their influence on life-safety consequence severity.

Arctic shipping risks and accident frequencies have been evaluated based on historical accident data, but as presented, the data is insufficient to support modelling life-safety consequence severity. Under reporting and inconsistency in the classification of maritime accidents contributes to a gap in the existing research literature [17]. Reviews of Arctic shipping risks and associated studies are provided by Fedi et al. [8] and Kum and Sahin [18].

Recent trends for Arctic shipping accidents demonstrate the need for enhanced risk mitigation. Arctic ship accidents have increased dramatically over the last fifteen years, from 8 accidents reported in 2006 [17] to a peak of 71 accidents in 2017 [19]. A slight decrease has been observed in 2018 and 2019, with 43 and 41 reported accidents, respectively [20]. Accident statistics from 1995 to 2004 are presented in an Arctic Council report [21], excluding data from the Russian Arctic. Vessel sinking occurred in 43 of the 293 accidents reported (15%). These datasets did not provide information on evacuations or associated fatalities.

Specific to the Canadian Arctic, a Council of Canadian Academies report [22] presented accident data for cargo vessels between 2004 and 2015. A total of 451 accidents occurred in northern Canada, of which 8 (2%) resulted in a fatality and 58 (13%) resulted in a serious injury. The number of POB associated with these accidents was not available. Kubat and Timco [23] presented an analysis of ship damage events resulting from ice impacts in the Canadian Arctic between 1978 and 2002. Vessel sinking occurred in 3 of the 125 reported accidents (2%). It is presumed that evacuation was required. A large hole was produced in 21 (17%) of the events, but it is not known if any resulted in evacuation.

Data and information on ship accidents in the Russian Arctic is provided by Fedi et al. [17] and Marchenko [24]. Fedi et al. [17] provided a structured analysis of accidents in Russian waters from 2004 to 2017, following IMO Casualty Investigation Code [25] definitions. Accidents were analyzed and classified based on consequence severity categories: marine incident, marine casualty, serious casualty, or very serious casualty. Of the 36 accidents analyzed, 2 (6%) were classified as very serious casualty, resulting in sinking or death.

Climatic conditions were a factor in both of these events. No information was provided on evacuations or associated fatalities. Marchenko [24] did not provide a database but rather detailed narratives of accidents since 1900. The level of detail presented for each accident is variable, but aimed to cover causal factors, environmental conditions, technology considerations, and actions of the crew.

Kum and Sahin [18] provided a root cause analysis for a limited dataset of 65 Arctic ship accidents that occurred between 1993 and 2011. Results suggest accident to person is the most common cause of accident and that crew competency is a predominant causal factor. Accidents to person were associated with injuries sustained onboard the vessels. Injuries and fatalities resulting from an evacuation were not captured.

The described datasets and studies provide insight into ship accident frequencies, causal factors, and consequence severity for Arctic waters. While this information promotes more informed risk-based decision-making, the data does not support an evaluation of accidents that resulted in evacuation nor associated fatalities.

Several studies have investigated the factors that influence the potential for loss of life during evacuation and rescue in Arctic waters. Factors include SAR capability and capacity, response time, and the ability of evacuees to survive until rescue.

SAR services play a central role in mitigating life-safety risk of Arctic ship accidents. SAR services encompass monitoring, communication, and coordination of SAR functions, including locating and retrieving persons in distress, providing medical assistance, and delivering them to a place of safety [26].

An agreement on cooperation on Arctic SAR was established between Arctic Council member nations. Member nations agree to establish and maintain effective Arctic SAR services and provide cross-border assistance in Arctic SAR efforts [27]. The establishment of a legally binding Arctic SAR agreement marked a turning point in cooperation between Arctic nations, not only for SAR, but for broader Arctic governance. This was evidenced by the subsequent establishment of the Arctic oil spill response agreement [28,29].

Despite the establishment of the Arctic SAR agreement, there remains a need for continued improvement, particularly around competency and cooperation. The Finnish Border Guard investigated challenges that face Arctic SAR services and made recommendations to enhance Arctic SAR capabilities and cooperation [30]. Key challenges included long distances, severe weather and climatic conditions, poor communication, a lack of SAR infrastructure, inadequate evacuation and survival equipment, and a lack of Arctic communities with sufficient resources to host survivors. Recommendations included enhancing cooperation and competency through data and knowledge sharing, establishing working groups and committees, and testing equipment and procedures through SAR exercises.

High POB evacuations, such as cruise ships, may exceed SAR capacities. The efficacy of large scale Arctic SAR operations was investigated by Schmied et al. [31]. A key finding was that the situational awareness during SAR operations for both personnel on-scene and ashore needs to be improved. Enhanced cross-institutional competence sharing and education on decision-making, teamwork, and leadership was suggested to address this gap.

Emergency response capacities influence life-safety consequence severity of Arctic ship accidents. Marchenko et al. [1] evaluated the likelihood and life-safety consequence severity of different accident types for the Atlantic Arctic. Analysis focused on regional SAR capacities. It was demonstrated that consequence severity depends on causal factors of the accident, scale of the accident, and location. Implications for Arctic SAR include the need to allocate resources to high traffic regions, enhance SAR equipment for operation in the Arctic environment, and improve coordination of international SAR resources. A five-point Likert scale index was used to model consequence severity (insignificant, minor, moderate, significant, or serious), but the number of fatalities associated with each severity level were not defined.

Emergency response times for eight regions of the Canadian Arctic were evaluated in a National Research Council of Canada study [32]. Response time depends on proximity to SAR infrastructure and assets, which has a seasonal and regional variance. Response times ranged from 13 hours in southern latitudes to a maximum of 237 hours in the more northern latitudes. A subsequent phase of this project recently evaluated the impact that vessels of opportunity have on response times in the Canadian Arctic [33].

The performance of LSAs in the Arctic will influence the ability of evacuees to survive until rescue [1,30]. The SARex exercises [34-36] investigated procedures for escape, evacuation, and rescue, survival, and SAR, and tested the performance of LSAs under Arctic conditions. The exercises highlighted significant gaps in existing equipment and provided insight into how to achieve the functional requirements for LSAs provided in the Polar Code. The efficacy of different Arctic personal protection equipment (PPE) in preventing hypothermia was evaluated by Power et al. [37]. They conclude that the majority of Arctic maritime PPE provides inadequate thermal protection to prevent hypothermia for expected Arctic response times. Thermal performance of PPE is further deteriorated if evacuees become wet or exposed to wind.

While these studies provide insight into SAR capability and survivability in the Arctic, there remains a gap in evaluating the expected number of fatalities resulting from a ship evacuation in Arctic waters.

3.3.4. Elicitation of expert knowledge

A challenge in assessing Arctic life-safety risk is the relative lack of data in comparison to non-Arctic maritime operations [1,8,17]. This dearth of accident data limits the use of conventional risk assessment methodologies, which rely on empirical event probabilities and fatality statistics [1]. In the absence of sufficient accident data, the elicitation of expert knowledge is often employed and has become standard practice in maritime risk assessments.

3.4. Method

A two-phased mixed methods design was employed to elicit expert knowledge to inform the development of a life-safety consequence model for Arctic ship evacuations. The first phase is qualitative, with participants interviewed to identify the factors that influence the potential for loss of life following an Arctic ship evacuation. The second phase is quantitative but still subjective. Experts rated the life-safety consequence severity level posed by different ship types and evacuation scenarios.

3.4.1. Phase 1: Semi-structured interviews

The Phase 1 interviews elicited knowledge and perspectives on the factors that influence the potential for loss of life during ship evacuations in the Arctic. Interviews were semi-structured, meaning that some questions were scripted, while additional probing questions were used to gain a deeper understanding of the subject matter. The interview guide is presented in Table 3.2.

Table 3.2. Phase 1 interview guide.

1. Introduction
1.1 What are some of the challenges of a ship evacuation in Arctic waters, in comparison to non-Arctic waters?
2. Perceived severity and influencing factors
2.1 What factors contribute to the potential for loss of life during the evacuation and rescue of a ship in Arctic waters?
2.2 Do certain ship types pose a greater potential for loss of life should evacuation and rescue occur in Arctic waters?
2.3 Does the operational profile of a ship influence the potential for loss of life should evacuation and rescue occur in Arctic waters?
2.4 Are there Arctic regions that pose a greater potential for loss of life should evacuation and rescue occur in Arctic waters?
3. Closing
3.1 Considering life-safety for Arctic shipping, what are your biggest concerns?
3.2 Is there anything else you would like to add regarding life-safety for Arctic ships?

Participants were recruited through convenience and snowball sampling, relying on the professional networks of the research team. Experts were recruited from the fields of Arctic policy and regulation, seafaring, research and academia, and ship design/consulting. Information on the backgrounds and years of experience of the participants for both phases is provided in Table 3.3.

Table 3.3. Participant backgrounds.

Career	Years of experience	No. of Participants, Phase 1	No. of Participants, Phase 2
Seafaring	25+	4	4
	15 – 20	1	1
	10 – 15	1	1
	0 – 5	1	1
Research/ Academia	25+	1	1
	20 – 25	3	1
	10 – 15	1	3
Policy/ Regulation	25+	2	1
	10 – 15	1	1
Ship design/ Consulting	25+	1	1
	10 - 15	0	1

Interviews were held over videoconference with the audio and video recorded. The audio recordings were transcribed verbatim. Participants reviewed their transcripts prior to analysis to ensure accurate transcription and to provide them the opportunity to modify their responses.

Interview transcriptions were analyzed using thematic analysis. Themes are reoccurring elements across multiple interviews that have a degree of salience in relation to the research questions [38].

Interview transcripts were first coded. Segments of text were categorized to a given code that captures the meaning of what was said by the participant. Some codes were established a priori while other codes emerged over the course of the analysis. The same segment of text can fit multiple codes and is referred to as a code intersection.

Once all interviews had been coded, the most frequently referenced codes and code intersections were analyzed. It is through analysis of the coded data that themes emerged.

Thematic data saturation was used to dictate the necessary number of interviews [39]. It refers to the point at which additional interviews produce no new insights or themes. Thematic saturation can only be determined after conducting the interviews and analyzing the data.

For the current study, a total of sixteen participants were interviewed. Once all interviews were complete, a base analysis of ten interviews were analyzed. Following the base analysis, additional interviews were analyzed until three consecutive interviews produced no new data. Thematic saturation was established after analysis of thirteen interviews, however all sixteen interviews were analyzed and included in the results.

3.4.2. Phase 2: Rating surveys

The results of the thematic analysis informed the development of the Phase 2 survey. Survey details are provided in the Appendix A. Participants first rated risk factors for their level of influence on response time, evacuee survivability, and the potential for loss of life following an evacuation. The level of influence was evaluated using a five-point Likert scale from 'No influence' to 'Extreme'.

Participants then rated evacuation scenarios based on the perceived level of life-safety consequence severity they pose. Nineteen scenarios were developed based on the themes that emerged from the Phase 1 interview data. Themes are related to factors that influence the potential for loss of life. The factors and associated levels used to define the scenarios are presented in Table 3.4. Five ship types with associated POB numbers were evaluated for each scenario (Table 3.5).

Table 3.4. Phase 2 factors used to define evacuation scenarios.

Factors	Levels			
Season	Summer		Winter	
Ice conditions	Sea ice		Open water	
Wind/sea state	Calm		Severe	
Evacuation	Controlled		Uncontrolled	
Response time	12 hrs	24 hrs	2 days	5 days

Table 3.5. Phase 2 ship types and POB numbers evaluated for evacuation scenarios.

Ship type	POB
Passenger vessel (e.g. expedition cruise ship)	250
Passenger vessel (e.g. standard cruise ship)	1,000
Cargo vessel	25
Fishing vessel	10
Pleasure craft	10

Life-safety consequence severity was evaluated using the five-point severity scale recommended in the FSA, and presented in Section 3.3.1 (Table 3.1). Individual survey results are combined to produce resultant values for influence and severity.

Sixteen participants completed the Phase 2 survey. This was largely the same group of experts who participated in the Phase 1 interviews, with the exception of three individuals. The three new participants who joined Phase 2 each have 10 – 15 years of experience. Two have careers in research and academia, and one has a career in consulting. Three participants from Phase 1 did not participate in Phase 2. Two of these participants have 20

– 25 years of experience in research and academia. The third participant who left after Phase 1 has 25+ years of experience in policy and regulation. Details on participant background for both phases are provided in Table 3.3.

3.4.2.1. Level of agreement between experts

Evaluating agreement among experts is recommended in the FSA guidelines to increase transparency in data produced from expert opinion [9]. The FSA guidelines recommend the use of Kendall's concordance coefficient, however this is only applicable to ranked data, in which a respondent orders or compares items relative to one another.

For the current study, experts provided rated data, as opposed to ranked data. Experts rated items by assigning a value to each particular item. The same value could be used more than once and there was no comparison or ordering of items relative to one another.

The level of agreement between expert ratings was evaluated using Randolph's free-marginal multi-rater $kappa_{free}$ coefficient [40]. Randolph's $kappa_{free}$ is a variation of Fleiss' kappa ($kappa_{fixed}$) and is applicable to studies in which raters are not restricted on the number of cases that must be assigned to each rating category. The $kappa_{free}$ coefficient has a range of -1 to 1, with 1 representing total agreement and -1 representing no agreement. A value of 0 represents a level of agreement that would be expected to occur by chance.

To illustrate the calculation of the Randolph's $kappa_{free}$ coefficient, consider a scenario in which n experts, rate N ship types (cases), using k severity categories. The overall percent agreement P_o among the experts is calculated using Eq. 3.1, where n_{ij} is the number of experts who assigned the i^{th} ship type to the j^{th} severity category. The percent agreement that would be expected by chance P_e is calculated using Eq. 3.2. Randolph's *kappa*$_{free}$ coefficient is calculated using Eq. 3.3.

$$P_o = \frac{1}{Nn(n-1)}\left(\sum_{i=1}^{N}\sum_{j=1}^{k} {n_{ij}}^2 - Nn\right) \tag{3.1}$$

$$P_e = {}^{1}\!/_{k} \tag{3.2}$$

$$kappa_{free} = \frac{P_o - P_e}{1 - P_e} \tag{3.3}$$

The experimental design and participant recruitment strategy for this study received ethics review and approval by the Memorial University Interdisciplinary Committee on Ethics in Human Research (ICEHR) and is in compliance with the guidelines of the Tri-Council Policy Statement on Ethical Conduct for Research Involving Humans (ICEHR number 20210767-EN). The ICEHR approval letter is presented in Appendix B.

3.5. Results and analysis

The following section presents a scenario-based life-safety consequence model for Arctic ship evacuations. Section 3.5.1 presents a conceptual framework for consequence severity based on the Phase 1 interview data. Section 3.5.2 discusses the level of influence that factors have on the severity of an evacuation. Section 3.5.3 provides an evaluation of consequence severity for different evacuation scenarios. Sections 3.5.2 and 3.5.3 are based on the Phase 2 survey data.

3.5.1. Conceptual framework for consequence severity

Many dynamic and interrelated factors contribute to the outcome of an Arctic ship evacuation. Themes that emerged from the Phase 1 interviews are related to the factors that influence the potential for loss of life.

The themes and their relationships are presented as a conceptual framework for life-safety consequence severity for Arctic ship evacuations (Figure 3.1). The elements of the conceptual framework represent influencing factors. The branches of the conceptual framework represent paths of influence, with elements being directly influenced by those below it.

The crux of any successful ship evacuation is the ability of evacuees to survive until rescue. Response time and survivability are the primary factors identified by interview participants as influencing consequence severity and thus represent the two main branches of the conceptual framework.

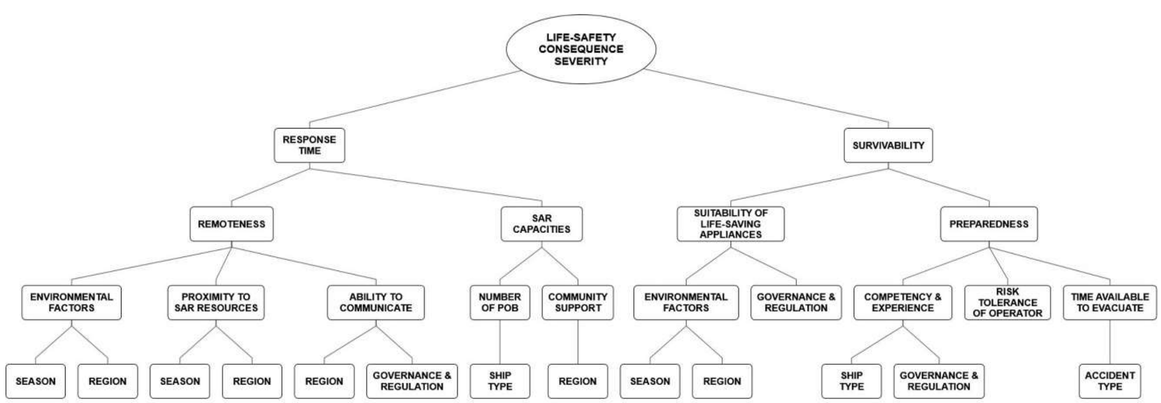

Figure 3.1. A conceptual framework for life-safety consequence severity for Arctic ship evacuations.

A number of influencing factors define response time and survivability. At the most granular level, there are six common influencing factors: season, region, governance and regulation, ship type, risk tolerance of the ship operator, and accident type.

3.5.1.1. Response time

Response time is defined as the total time from when a ship places a distress call to when evacuees are rescued and brought to a place of safety. It includes the time required for emergency responders to arrive on-scene and the on-scene time required to retrieve evacuees and transport them to a place of safety. Nearby communities may act as places of safety.

Arctic response times are generally longer compared to non-Arctic regions. The primary factors identified as influencing response time are the remoteness of the accident location and the capacity of SAR resources to effectively respond to the scale of the accident.

3.5.1.1.1. Remoteness

Three factors define remoteness: environmental factors that impede emergency response operations, proximity of SAR resources to the accident location, and the ability to communicate.

Environmental factors

Severe weather and reduced visibility can prevent the use of air-based SAR assets. The presence of sea ice can limit the use of fixed wing aircraft and increase transit times for marine-based SAR assets. Once on scene, the presence of sea ice, extended periods of darkness, and severe metocean conditions can complicate the location and retrieval of survivors and increase the time required to shuttle survivors to safety. Severe weather can occur at any time throughout the Arctic, but environmental factors generally deteriorate at more northern latitudes and during the winter season. Expected response time and consequence severity increase as environmental conditions become more challenging.

Proximity to SAR resources

Proximity of SAR resources to the accident location influences the time required for emergency responders to arrive on-scene. SAR resources include dedicated air- and marine-based assets, potential vessels of opportunity, and any local SAR assets deployed from nearby communities. Longer distances will require air-based assets to make multiple stops on route for refueling and crew rest/changeover. Participants note that nearby vessels of opportunity can arrive on-scene quickly but are often limited in their ability to rescue evacuees. Expected response time and consequence severity increase the farther SAR resources are from the accident location.

Participants note the availability of SAR assets is quite different in the Canadian/US Arctic from the Northern Sea Route and the Baltic Sea. SAR assets are strategically stationed throughout the Canadian Arctic during the summer shipping season. The majority of these are located in more southern latitudes to support higher traffic densities. During the winter season, there are no dedicated SAR assets stationed in the Canadian Arctic and assistance from vessels of opportunity is less likely.

In contrast, along the Northern Sea Route and in the Baltic, there is more SAR infrastructure in place to support shipping operations. There are also higher traffic densities and a greater availability of vessels of opportunity. This decreases expected response times and consequence severity.

Ability to communicate

The ability to send a distress call, report accident location, and maintain communication with emergency responders is a key factor influencing remoteness and response time. Interview participants noted that while communication technology continues to advance, communication availability remains limited in certain regions. Interruptions in communication will increase expected response time and consequence severity.

Frequent reporting provides authorities with a better indication of a distressed vessel's last known position. This reduces the search area and improves response time. Most vessels operating in the Arctic are required to regularly report to vessel traffic services, however the regulations do not apply to all vessels. Smaller boats, such as fishing vessels and pleasure craft, are not required to maintain regular communication with authorities. This increases expected response times.

3.5.1.1.2. SAR capacity

SAR capacity refers to the maximum number of evacuees that can be effectively rescued by all available SAR resources. An insufficient SAR capacity will increase on-scene response time and the expected consequence severity.

Number of POB

The number of POB dictates the required SAR capacity. High POB vessels will likely be beyond available SAR capacities. High POB Arctic vessels are almost exclusively passenger vessels. Many interview participants believe that the evacuation of a cruise ship in the Arctic is a worst-case scenario. Illustrated by a participant:

> *"… for sheer volume or magnitude of the incident, a cruise ship is the worst case scenario"*

Community support

Survivors are likely to be shuttled to nearby communities. Local communities act as a safe haven for survivors, providing shelter, food, water, and medical resources. Participants note that high POB evacuations can overwhelm the resources of a single community, requiring the resources of multiple communities. The distance to nearby communities and the potential need to shuttle survivors to multiple communities will increase expected response times and consequence severity.

There is significant concern among some participants of the potential negative impacts of ship evacuations on Arctic communities, such as inundating community services and depleting resources. While this does not directly influence the consequence severity of evacuees, it is seen as an ancillary consequence of an Arctic ship evacuation. One participant stated:

> *"… the Northwest Passage, it's public. Who's going to help us out in the event of an emergency, it's going to fall on Canada and it's going to be our northern communities that suffer the consequences of accidents"*

3.5.1.2. Survivability

Survivability is the ability of evacuees to survive in the environment into which they have evacuated. The adequacy of LSAs available onboard and the degree to which individuals are prepared for the evacuation will influence survivability.

3.5.1.2.1. Performance of life-saving appliances

LSAs include survival craft, associated survival equipment, and the PPE donned prior to evacuation. Two key factors influencing the performance of LSAs are the environment in which they are used and the regulatory guidance for Arctic-specific LSAs.

Regulation & governance

Regulations require a vessel to have survival craft capacity and a sufficient number of immersion suits for all POB. Survival resources provided to evacuees, including thermal protection and rations, should be adequate for the maximum expected time to rescue [10].

A major concern among interview participants is LSAs not satisfying the functional requirements provided in the Polar Code. LSAs currently in use are not designed and tested for all Arctic conditions. It has been demonstrated that LSAs are inadequate to support survival for the Polar Code required five-day maximum expected time of rescue [34,37]. As explained by a participant:

> *"If you're going to be picked up in the course of hours, then the LSAs are adequate for that. If you're going to have to wait for the five day [maximum] which is specified in the Polar Code, then that's a very different set of circumstances."*

Environmental factors

Hypothermia due to cold temperatures is a major risk to survival following evacuation. Participants raised concerns that the thermal insulation provided by immersion suits and survival craft is insufficient for longer rescue times. There is less insulation provided by life rafts than lifeboats.

Sea ice is another factor affecting the performance of LSAs. Sea ice can damage survival craft during launch or prevent launching altogether. Once in the water, sea ice can prevent maneuvering survival craft away from the evacuated ship. Internal pack ice pressure can crush survival craft. While sea ice is a major concern, some participants noted that evacuation onto a stable ice cover could be an optimal evacuation scenario. The performance of LSAs will degrade in more severe climates and weather, such as in more northern latitudes and during the winter season.

3.5.1.2.2. Preparedness

The degree to which personnel are prepared to evacuate will influence survivability. Key factors influencing preparedness are competency and experience, risk tolerance of the ship operator, and time available for evacuation.

Competency & experience

Crews with higher levels of training and experience contribute to reduced consequence severity.

Professional seafarers have training in evacuation and survival, but most training is not specific to the Arctic. Most seafarers will have never actually evacuated a ship in Arctic waters. Participants note a distinction between crews with Arctic experience and those with no experience operating in the Arctic. Ship crews that regularly operate in Arctic waters will be better prepared to adapt LSAs and evacuation procedures to suit the evacuation scenario.

Several participants expressed concern over the training requirements for officers in charge of navigational watch introduced through the Polar Code (i.e. ice navigators). The presence of an experienced ice navigator not only contributes to the prevention of accidents, but also to the level of preparedness during emergencies in Arctic waters. The training requirements introduced through the Polar Code allow seafarers to obtain polar navigation certification with minimal training and Arctic sea time. It is thought that the new requirements have eroded the quality and level of experience of ice navigators. One participant stated:

> *"There's been a lot of discussion, a lot of concern raised by the master mariner community ... and other organizations as to whether the standard of training for Arctic navigators, polar navigators, is high enough. I suspect it isn't. I think that there is a very limited requirement for having actually actively navigated in polar waters before you're allowed to do so. And so a lot of people don't necessarily meet a very high bar."*

Passenger vessels (e.g. cruise ships) present several challenges that complicate evacuation and survival. Passengers have no experience in evacuation or survival, they often have a higher average age in comparison to seafaring crews, and they may have mobility issues. These factors, combined with higher POB levels, create the potential for increased consequence severity should an evacuation of a passenger vessel occur. As described by a participant:

> *"For instance 25-30 sailors on a bulk carrier or a fishing vessel may be better equipped to withstand the rigors of an evacuation in Arctic water, than elderly passengers on a cruise ship."*

Risk tolerance of the ship operator

The risk tolerance of the ship operator will dictate the extent to which they adopt risk-mitigating measures and go above regulatory requirements to ensure safe operations.

A risk mitigating best practice that was highlighted multiple times throughout the interviews is the coordination of a support vessel in close proximity when operating in remote regions. This may be referred to as an escort vessel, a sister vessel, or the buddy system. Participants highlighted many examples of this. It is a common practice among cruise ship operators in both the Arctic and Antarctic. The Crystal Serenity travelled with the RRS Ernest Shackleton on its recent voyages of the Northwest Passage. The Canadian Coast Guard made several recent expeditions to the North Pole with the CCGS Terry Fox and the CCGS Louis St-Laurent travelling together. Companies operating cargo vessels off Baffin Island provide their own icebreaker escorts. One participant even highlighted that this is not a new practice. The Erebus and the Terror travelled together during the Franklin Expedition in 1845. The benefit of a sister vessel was realized when the Akademik Ioffe ran aground in the Gulf of Boothia in 2018. Its sister vessel, Akademik Sergey Vavilov, was able to tow it to safety.

There was an amount of contradiction between interview participants on the risk tolerance of cruise operators. Cruise ships tend to venture off regular, charted Arctic shipping routes, into more remote regions, and in close proximity to e.g. calving glaciers. This increases the expected consequence severity should an accident occur. In contrast, several participants note that cruise ships typically have robust safety management plans and operate conservatively near sea ice.

The Crystal Serenity voyages of the Northwest Passage in 2016 and 2017 are considered to have set a very high standard for safe Arctic cruise operations. The operator coordinated extensively with Canadian and US regulators in planning the voyage. They went above the regulatory requirements to mitigate risk. They trained and carried additional ice navigators, they carried additional emergency equipment, and they travelled with a support vessel.

While some cruise operators have demonstrated a strong safety culture, it comes with a cost. Participants worry about complacency. Future cruise operators may begin to cut corners on safety in order to provide a more competitive price to passengers. The high degree of regulatory oversight demonstrated on early cruise operations may decrease.

Time available to evacuate

The time available to evacuate will contribute to survivability. Many participants note that the safest place is onboard the ship and an evacuation is a last resort. Assuming an evacuation is necessary, a controlled evacuation provides crew and passengers with adequate time to don PPE and insulating layers, take all necessary items for survival, and evacuate in a safe and controlled manner. An uncontrolled evacuation, such as a rapid capsizing or significant onboard fire, may lead to personnel evacuating the vessel with insufficient survival necessities and PPE. The nature of the ship casualty will dictate the time available to evacuate and an uncontrolled evacuation will increase the consequence severity.

3.5.2. Levels of influence

The critical factors that emerged during the Phase 1 interviews shaped the Phase 2 survey questions and scenarios. Survey participants rated factors for their level of influence on three different aspects of consequence severity: expected number of fatalities, response time, and survivability. Expected number of fatalities is the measure of life-safety consequence severity, while response time and survivability emerged from the Phase 1 interviews as the primary factors influencing consequence severity.

A list of fourteen factors were selected for evaluation of their level of influence on the expected number of fatalities resulting from an evacuation. Factors were selected based on the themes that emerged from the Phase 1 interviews. Participants rated levels of influence using a five-point Likert scale from ‘No influence’ to ‘Extreme’ influence. The average ratings across all participants are presented in Figure 3.2. Standard deviation bars are plotted for each factor.

Response time has the most significant influence on the expected number of fatalities, with longer response times leading to more severe outcomes. Time available to evacuate and temperature have the next highest levels of influence. An uncontrolled evacuation and colder temperatures will lead to greater numbers of expected fatalities.

The number of POB is evaluated as having a relatively low level of influence. This is surprising given that many participants suggest a cruise ship evacuation in the Arctic would be a worst-case scenario due to the high POB level.

A subset of factors were evaluated for their level of influence on response time and survivability. Average ratings are presented in Figure 3.3 and Figure 3.4, respectively. Standard deviation bars are plotted for each factor.

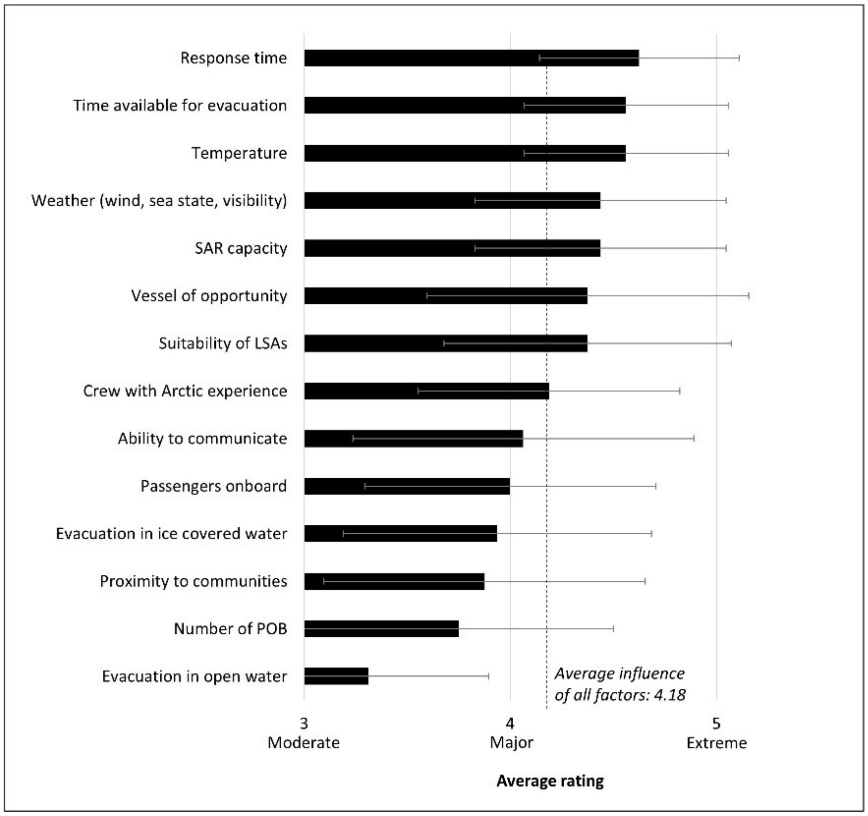

Figure 3.2. Level of influence on expected number of fatalities.

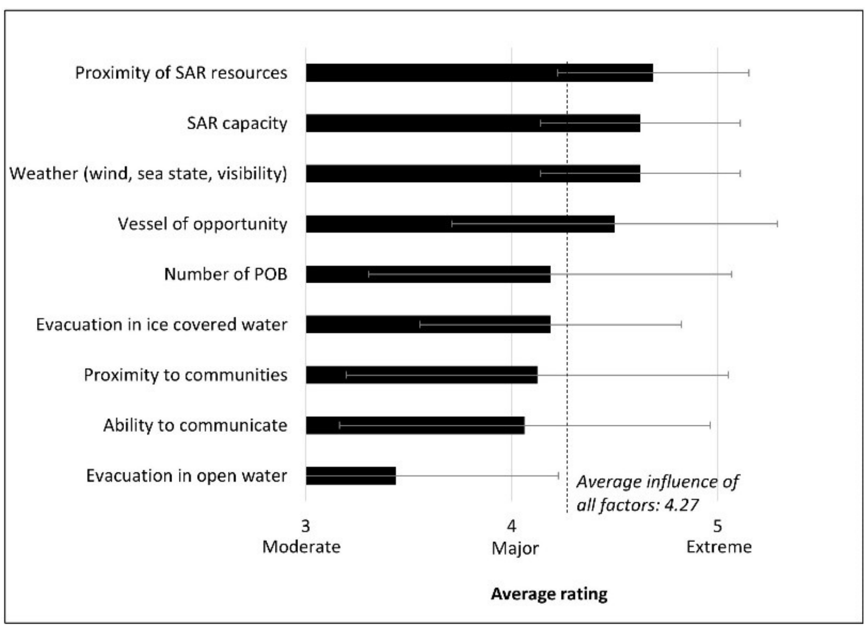

Figure 3.3. Level of influence on response time.

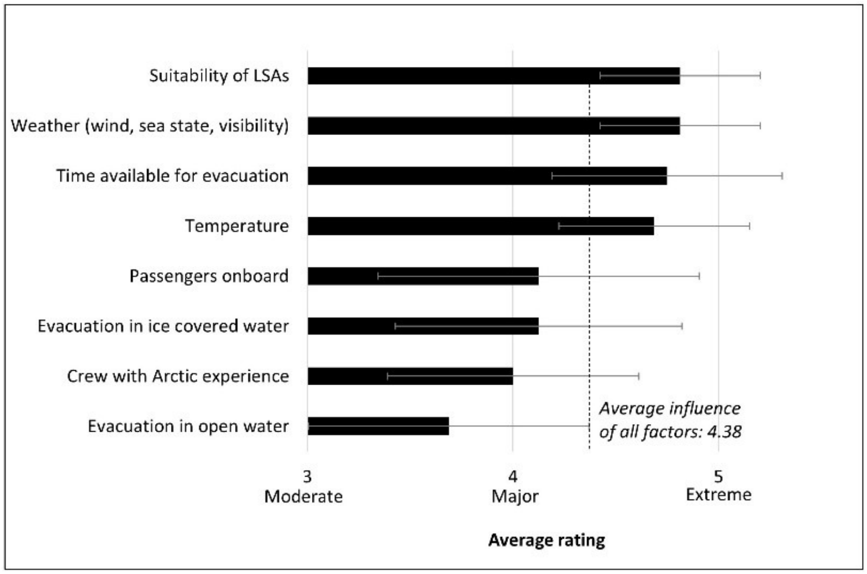

Figure 3.4. Level of influence on survivability.

Proximity of SAR resources, available SAR capacity, and weather severity at the time of the evacuation have the highest levels of influence on response time. Response time increases with the distance SAR resources have to travel. Longer distances may require air-based assets to stop to refuel or for crew changeover, creating further delays. Insufficient SAR capacity for the scale of the accident will increase the on-scene response time. Severe weather, such as high winds and sea states, and reduced visibility, increase response time by delaying deployment and transit of SAR assets and complicating the on-scene rescue effort.

Suitability of LSAs for the environment in which evacuation occurs, weather severity, and time available to evacuate have the highest influence on survivability.

Suitability of LSAs and weather severity are closely linked in their influence on survivability. The presence of sea ice can damage or prevent the launch of survival craft and LSAs may need to be adapted ad hoc to suit the evacuation scenario. Survival craft and PPE provide insufficient thermal protection to support extended survival times in Arctic conditions. High wind and sea states and precipitation increase the risk of evacuees getting wet. Once wet, the increased onset of hypothermia further decreases survivability.

The time available to evacuate has a significant influence on survivability. A rushed and uncontrolled evacuation may leave personnel with only partial PPE and survival equipment and less likely to survive extended response times.

Experts rated factors for their level of influence on expected number of fatalities, response time, and survivability. The level of agreement between experts was measured for the three ratings. An average kappa value of 0.32 indicates a 'fair' level of agreement.

3.5.3. Scenario-based consequence severity

Nineteen evacuation scenarios (B1 to B19) were evaluated and average severity ratings are plotted in Figure 3.5 to Figure 3.7. The complete list of scenarios is provided in the Appendix A. Scenarios are displayed on the abscissa. A baseline scenario (B1) is included in each plot for reference. The factors used to define each scenario are presented in the boxes directly below the axis. For clarity, scenario factors that are different from the baseline are underlined and bold. Severity indices are presented on the ordinate. Standard deviation bars are plotted for each scenario.

Several trends are observed across all scenarios. Passenger vessels pose the highest life-safety consequence severity. The 1000 POB vessel poses a significantly higher severity level than the 250 POB vessel. The cargo vessel (25 POB) is evaluated as posing the lowest severity level in nearly all scenarios, despite having more POB than the fishing and pleasure vessels (10 POB each).

The effect of response time on consequence severity is presented in Figure 3.5. Response times range from 12 hours to 5 days and all other factors are held constant. The baseline scenario (B1) has a response time of 12 hours. Average severity values are evaluated in the range of 1 (Minor) and 2 (Severe). Minor or severe injuries are expected for all vessels.

Consequence severity increases with response time. At a response time of 5 days (B4), severity values of just over 3 (Significant) are estimated for the cargo, fishing, and pleasure vessels. This corresponds to multiple severe injuries or single digit fatalities. A severity value of just under 4 (Catastrophic) is estimated for the 250 POB passenger vessel. This corresponds to single digit fatalities, although approaching fatalities on an order of magnitude of tens. A severity value between 4 (Catastrophic) and 5 (Disastrous) is estimated for the 1000 POB passenger vessel, corresponding to fatalities between orders of magnitude of tens and hundreds.

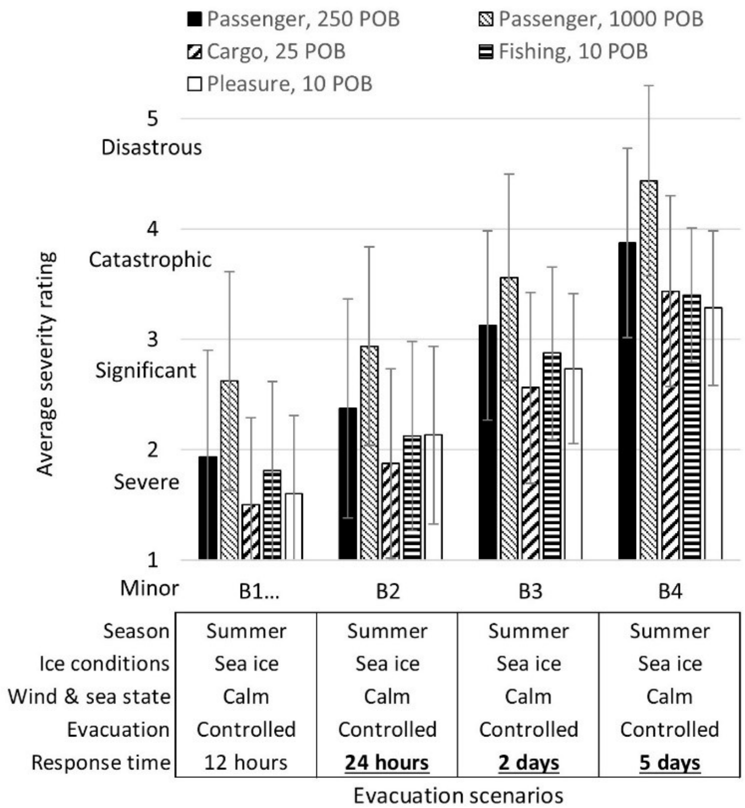

Figure 3.5. The effect of response time on the average life-safety consequence severity.

The effect of season on life-safety consequence severity is presented in Figure 3.6 and Figure 3.7. Summer evacuation scenarios are presented in Figure 3.6 (B1 and B5 to B11). Winter evacuation scenarios are presented in Figure 3.7 (B12 to B19). The baseline scenario (B1) is included for reference. A constant response time of 12 hours is used for these scenarios.

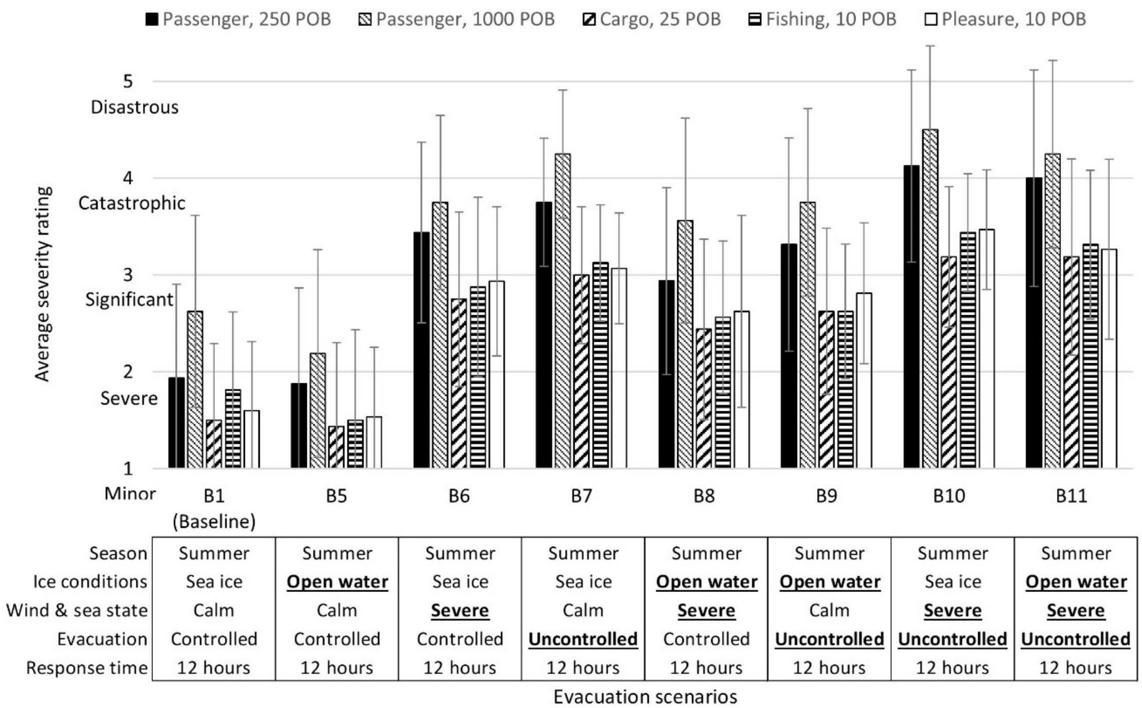

Figure 3.6. Average life-safety consequence severity, summer scenarios.

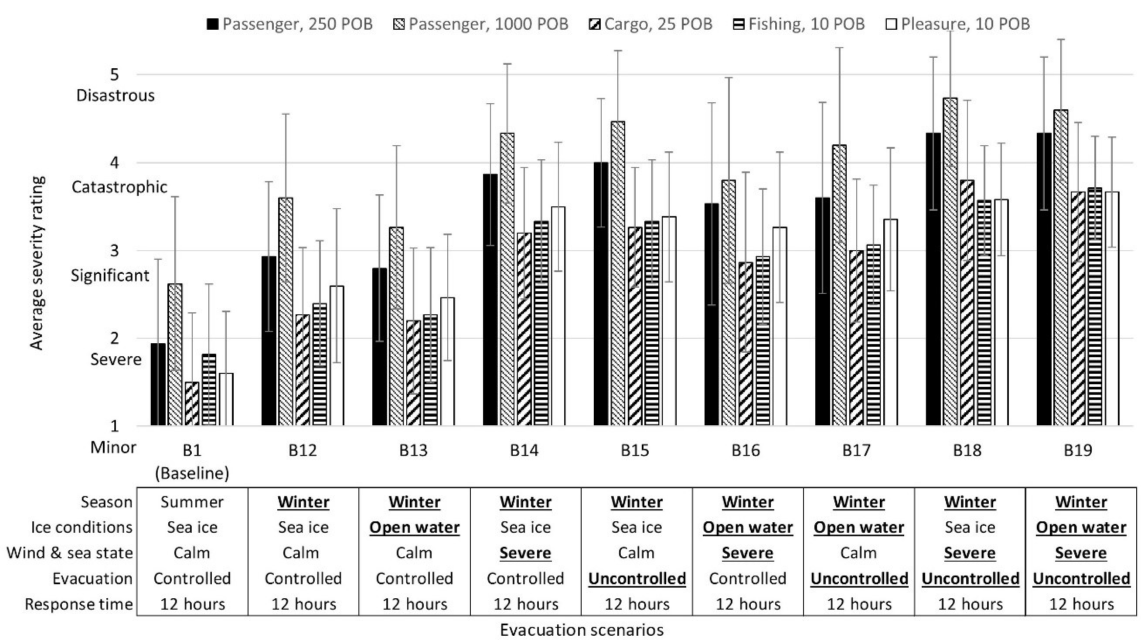

Figure 3.7. Average life-safety consequence severity, winter scenarios.

Trends are common across seasons. An evacuation in open water is generally perceived to have an ameliorating effect on severity level compared to an evacuation into sea ice. The lowest severity level for both seasons is associated with a controlled evacuation in calm weather and open water (B5 for summer, B13 for winter). Aside from response time, an uncontrolled evacuation is the most significant contributor to increased consequence severity (B7 summer, B15 winter). Severe weather is the second most significant contributor (B6 for summer, B14 for winter). Factors have a compounding effect on the expected severity level, which is observed from the combination of an uncontrolled evacuation and severe weather.

Winter evacuations pose an increased severity level compared to summer scenarios. The worst-case scenario is an uncontrolled evacuation during winter in severe wind and sea state (B18 and B19 in Figure 3.7). In this scenario, a 1000 POB passenger vessel has an estimated severity value of 4.8.

The level of agreement between experts was measured for all scenario ratings. An average kappa value of 0.18 indicates a ‘slight’ level of agreement.

3.6. Discussion

3.6.1. Main findings and implications on Arctic marine policy and risk mitigation

Ship type has a significant influence on consequence severity following evacuation in Arctic waters. The majority of interview participants consider the evacuation of a cruise ship in the Arctic to be a worst-case scenario. This was validated by the survey results. A similar conclusion was drawn by previous studies [1,8,31]. Passenger vessels were judged to pose the highest life-safety consequence severity of all assessed ship types. Large numbers of POB, which can exceed available Arctic SAR capacity [1,31,34], and the fact that passengers have no experience in evacuation and survival, contribute to the increased severity level.

The Arctic SAR agreement [27] and Arctic SAR exercises [34-36] contribute to improved SAR capabilities, capacities, and international cooperation. Continued enhancement of competency and training for Arctic SAR services is necessary to mitigate the high consequence severity posed by the evacuation of a cruise ship in the Arctic [1,31].

Many participants noted the voyages of the Crystal Serenity through the Northwest Passage set a high bar for operational risk management and regulatory oversight. However, several participants expressed concern for the potential for complacency as more cruise ships enter the Arctic. In the Canadian Arctic, there is a need for enhanced governance and regulatory oversight of Arctic cruise ship operations, such as a single point of authority for permitting and the development of operational guidelines [3].

Arctic cruise ships often operate with a support vessel in close proximity when in remote regions. This is seen as an operational best practice for risk mitigation and should be promoted.

Cargo vessels pose the lowest life-safety consequence severity, even with a POB level above fishing and pleasure vessels. Participants attributed this to the competency and experience of professional seafarers and the regular reporting to maritime authorities required by larger commercial vessels.

Fishing and pleasure vessels pose a consequence severity above that of cargo vessels in most evacuation scenarios. Fishing vessels have a high accident and injury rate compared to other Arctic ship types [18] and fishing vessel traffic and vessel capacity have been increasing throughout the Arctic [1]. The exclusion of fishing and pleasure vessels from the Polar Code is cause for concern [8]. Excluded ship types are not required to satisfy Polar Code manning and training requirements nor to report regularly to vessel traffic services. The inclusion of fishing and pleasure vessels under the Polar Code may contribute to the mitigation of risk posed by these vessels.

Arctic ship operating criteria, such as imposed by the POLARIS methodology, should reflect the discrepancy in life-safety consequence severity posed by different ship types. The POLARIS methodology may be augmented to require ship types that pose a higher consequence severity (e.g. passenger vessels) to be operated more conservatively [16].

Response time was identified as one of the primary themes related to life-safety consequence severity. It was evaluated as having the greatest level of influence on the expected number of fatalities. Severity level increases dramatically with response time [1]. Even under optimal conditions (i.e. summer, calm weather, controlled evacuation), a response time of five days is expected to result in multiple fatalities for all assessed ship types.

Response time is influenced by proximity of SAR resources and SAR capacity [32]. While the establishment of the Arctic SAR agreement [27] is a significant step forward in improving the efficacy of Arctic SAR services [28], there remains a need to enhance the competency of and knowledge sharing between international SAR resources, particularly for high POB accidents [30,31].

Evaluating response time for specific regions and scenarios was out of scope. An evaluation of response times for the Canadian Arctic is provided by Kennedy et al. [32] and available through the National Resource Council of Canada (NRC) Canadian Arctic Shipping Risk Assessment System (CASRAS) database.

Survivability is the other primary theme related to life-safety consequence severity. Survivability is influenced by the suitability of LSAs for Arctic conditions and the degree of preparedness of the crew for evacuation and survival.

The suitability of LSAs has a significant influence on survivability. It was the most frequently referenced code in the analysis of the interview data. Many participants expressed their concern with the inadequacy of LSAs to support a safe evacuation and subsequent survival in the Arctic. The majority of Arctic LSAs and PPE do not provide sufficient thermal insulation to support survival for the Polar Code maximum expected time to rescue of five days [34-37]. Satisfying the functional requirements for LSAs stipulated in the Polar Code is a major gap in mitigating Arctic life-safety risk [34-36].

Evaluating the performance of specific LSAs for different evacuation scenarios was out of scope for the current study. The influence of LSA performance is considered implicit in the evaluation of consequence severity for the different evacuation scenarios. The SARex studies provided detailed investigations of the performance of LSAs under Arctic conditions [34-36].

The time available to evacuate is a sub-theme under survivability, influencing the level of preparedness of those onboard for evacuation and survival. It was rated to have the second greatest level of influence on the expected number of fatalities. Aside from response time, an uncontrolled evacuation, such as a rapid capsize, is the most significant contributor to increased consequence severity. This result aligns with the modelling approach for existing non-Arctic maritime risk assessments. Risk assessments completed in the SAFEDOR project modelled different sinking scenarios, e.g. slow sinking and a rapid capsize, and estimated the associated life-safety consequence severity [5-7].

The significant influence of preparedness on survivability emphasizes the importance of trained and experienced crews for Arctic navigation [1,8,18]. Crews with higher levels of training and experience contribute to reduced consequence severity. A lack of experience leads to increased risk of Arctic shipping accidents and consequence severity [1]. Although the Polar Code takes into account officer navigational competency [10], it does not address the increased risk of a crew with no Arctic experience [8] nor does it address the training and competency required to survive following evacuation [35].

In addition to concerns with the overall competency of the crew, several participants expressed concern over the officer navigational training requirements introduced through the Polar Code. Polar Code requirements allow seafarers to obtain polar navigation certification with minimal training and Arctic sea time. It is thought that the new requirements have eroded the quality and level of experience of ice navigators.

The Polar Code could further mitigate life-safety risk by requiring advanced competency and training for all crew, addressing the increased risk of crews with no Arctic experience, and increasing the requirements for officer navigational certification.

3.6.1.1. Benchmark findings

Despite a lack of accident data for the Arctic, interview participants referenced several accidents and evacuations that can be used as case studies to benchmark the findings of the current study. Existing studies in the research literature also provide a means to benchmark findings.

Time available to evacuate and weather were evaluated to have significant levels of influence on the expected number of fatalities. An uncontrolled evacuation and severe weather are significant contributors to increased consequence severity. The evacuations of passenger ferries MV William Carson and MV Estonia and the cruise ship MV Explorer provide case studies to compare to these findings.

The MV William Carson sank off the coast of Labrador in June 1977 with 128 POB. Weather was calm and there was sufficient time to mobilize the evacuation. Passengers and crew evacuated by lifeboats into sea ice. The response time was less than 12 hours. There were no fatalities [41].

Similarly, the MV Explorer sank in the Bransfield Strait in the Antarctic in November 2007 with 154 POB. Despite rapid flooding, the captain and crew executed a safe evacuation in ice by lifeboats and life rafts. Sea conditions were favourable at the time of evacuation and evacuees were rescued by two nearby vessels. The response time was approximately 6 hours. There were no fatalities [42].

Both the MV William Carson and the MV Explorer evacuations correspond with evacuation scenario B1. November is a summer month in the southern hemisphere. Evacuation of a passenger vessel with less than 250 POB would be evaluated in the range of 1 (Minor) and 2 (Severe). Minor or severe injuries would be expected.

In contrast, the MV Estonia capsized in the Baltic Sea between Finland, Estonia, and Sweden in September 1994 with 989 POB. Evacuation was in open water. The weather was severe with winds above 29 knots and a significant wave height of 3 to 4 meters. The vessel capsized rapidly. Despite a relatively fast response time of approximately 8 hours, there were 851 fatalities [43]. This corresponds with evacuation scenario B11. Evacuation of a passenger vessel with 1000 POB would be evaluated in the range of 4 (Catastrophic) and 5 (Disastrous). Multiple or large numbers of fatalities would be expected, with orders of magnitude between tens and hundreds.

These case studies demonstrate the influence that time available to evacuate and weather severity can have on the life-safety consequence severity of an evacuation and validate the scenario-based severity results from the current study.

The effects that time available to evacuate and number of POB have on consequence severity are supported by the results of the SAFEDOR project [6,7]. Expected numbers of fatalities were modelled as a percentage of vessel POB and ship survivability scenarios, i.e. slow sinking or rapid capsize. Expected fatalities for a slow sinking were estimated at

5% POB. Expected fatalities for a rapid capsize were estimated as high as 100% POB. While the SAFEDOR project was not specific to Arctic evacuations, it supports the finding that consequence severity increases with an uncontrolled evacuation and higher levels of POB.

3.6.1.2. Application to IMO FSA

The IMO FSA guidelines [9] provide a structured approach for policy-makers within IMO to assess maritime industry risks and evaluate proposed regulatory changes. The operational assessment required in the Polar Code to develop the PWOM and establish operating limits and procedures for the PSC is expected to follow the IMO FSA guidelines.

This section describes how the results of this study allow for the incorporation of expert-evaluated life-safety consequence severities in the IMO FSA and the risk-based operational assessment for Arctic ships. Accordingly, ship types and operating scenarios that pose higher life-safety consequence severity would be subjected to more conservative operating limits and procedures.

The IMO FSA guidelines [9] require estimates of life-safety consequence severity for assessment of maritime risk. Hazard identification is the first step of the FSA methodology. Relevant hazards are identified and prioritized based on risk index values. Risk index values are the summation of a frequency index and consequence severity index. The severity index corresponds to an expected number of fatalities. The average severity indices established in the current study can contribute to the prioritization of Arctic shipping hazards.

Risk analysis is the second step in the FSA methodology. Maritime risks are typically modelled using event trees. Event trees start with an initiating accident scenario and map different ship survivability end-scenarios (e.g. remains afloat, slow sinking, fast sinking). Frequencies of occurrence are assigned to each branch of the event tree and end-scenarios are assigned expected fatality values.

The current study has established order of magnitude estimates for equivalent fatalities for a range of evacuation scenarios. These estimates can support the modelling of event tree end-scenarios for Arctic risk analyses.

Consider an accident scenario for a 1000 POB passenger vessel, assuming summer operations, in sea ice and severe weather, and a response time of 12 hours. An event tree is modelled with three end-scenarios: remains afloat, slow sinking, and rapid capsize. If the vessel remains afloat, the expected fatality value is zero. Slow sinking (i.e. controlled evacuation) and rapid capsize (i.e. uncontrolled evacuation) correspond to scenarios B6 and B10, respectively. Slow sinking has a severity index of 3.75, which equates to equivalent fatalities between orders of magnitude of one and tens. Fast sinking has a severity index of 4.5, which equates to equivalent fatalities between orders of magnitude of tens and hundreds.

While these estimates can guide risk practitioners in establishing expected fatality estimates, sound judgement should be used with consideration for worst-case scenarios. The MV Estonia sinking provides an example of a worst-case scenario in which the rapid capsizing of the 989 POB vessel resulted in 851 fatalities [43].

3.6.2. Quality and limitations of the study

It is necessary to demonstrate and document validity, reliability, and overall quality of a qualitative study. The definitions for validity and reliability do not transfer directly between quantitative and qualitative research paradigms, but there are strategies to maximize validity and reliability in qualitative research. The methods taken for the current study are summarized below.

Establishing thematic saturation provides an indication of data validity and justifies the sample size of the study [44]. Variation in participant backgrounds contributes to the external validity of the results [45]. Prior to analyzing the interview data, participants reviewed and edited their interview transcripts. This is a form of member checking and contributes to the validity and trustworthiness of the research design and data [46]. The critical factors that emerged during the interviews shaped the survey questions and scenarios. This establishes reflexivity, contributing to the internal validity of the research design and the survey results.

Inter-coder reliability was tested by having a second member of the research team code interview data. The analyzed results were compared for agreement. Inter-coder reliability was tested on one complete transcript. An average agreement of 94% was measured across all coded content. Cohen's kappa, a statistical measure that considers the agreement that may occur by chance was measured at 0.46, which falls in the range of 'moderate' agreement [47].

Some limitations of the study should be highlighted. The majority of participants in this study have Canadian Arctic shipping backgrounds. Two participants have European shipping backgrounds (Baltic and Northern Sea Route). The results of this study may be most applicable to the Canadian Arctic, although effort has been made to highlight disparities with the Northern Sea Route and the Baltic.

While expert knowledge is a valuable source of data in risk assessment [9], Psaraftis [48] cautions that variables should be based on expert opinion only when necessary, the qualifications of experts should be scrutinized, and the methods used to elicit expert opinion and assign values should be validated. In assessing Arctic ship accidents and emergency response capacities, Marchenko et al. [1] highlighted that minor accidents can quickly escalate in severity due to the dynamic environmental conditions of the Arctic and the variable nature of accidents. Experts must be judicious in their assignment of categorical ratings of severity.

3.7. Conclusion

A scenario-based life-safety consequence model for Arctic ship evacuations was presented. The consequence model includes a qualitative conceptual framework and quantified consequence severities for different Arctic ship evacuation scenarios. The conceptual framework depicts the factors that influence the potential for loss of life resulting from a ship evacuation. The conceptual framework was developed based on expert knowledge elicited through semi-structured interviews. Scenario-based consequence severities were established based on expert evaluations elicited through a rating survey. Application of the results to the IMO FSA methodology was demonstrated.

Results show that the crux of a successful ship evacuation is the ability of evacuees to survive until rescue. Response time and survivability were identified as the primary factors that influence life-safety consequence severity of an Arctic ship evacuation. Ship type also has a significant influence on consequence severity.

Response time has the greatest level of influence on the expected number of fatalities following evacuation. Response time is influenced by SAR capabilities and capacities. SAR capacities often vary by region and season.

Survivability is influenced by the suitability of LSAs and level of preparedness of the crew for evacuation and survival. The majority of participants expressed concern with the suitability of LSAs for Arctic conditions. Existing LSAs and PPE are inadequate both for safe evacuation in all metocean conditions and to support survival for the maximum expected time to rescue.

The time available to evacuate influences the level of preparedness of those onboard for evacuation and survival. An uncontrolled evacuation is the second greatest contributor to an increase in the expected number of fatalities resulting from an evacuation in Arctic waters.

The influence of preparedness on consequence severity emphasizes the need for trained and experienced crews. While the Polar Code covers officer navigational competency, it does not address the increased risk of a crew with no Arctic experience. There is also concern that officer navigational training requirements introduced in the Polar Code are inadequate, allowing officers to obtain certification with minimal training and Arctic sea time.

Among Arctic ship types, the evacuation of a cruise ship is a worst-case scenario. The large numbers of POB can potentially exceed available Arctic SAR capacities. The MV Estonia disaster is a reminder that the worst-case can happen. In the Canadian Arctic, cruise operators and regulators have demonstrated strong operational risk management practices. However, there is the potential for complacency as the Arctic cruise industry grows.

Fishing vessels pose a relatively high life-safety consequence severity, above that of cargo vessels, yet fishing vessels are excluded from the Polar Code.

Implication to Arctic marine policy and risk mitigation have been discussed. Continued enhancement of competency, training, and international cooperation for Arctic SAR services is necessary to mitigate the life-safety consequence severity posed by Arctic shipping, particularly Arctic cruise operations. There remains a need for enhanced governance and regulatory oversight of Arctic cruise operations. This is necessary to address the potential for complacency as the industry grows.

Satisfying the Polar Code functional requirements for LSAs is a major gap in mitigating Arctic life-safety risk and requires continued research and development.

Future revision of the Polar Code should consider requiring advanced competencies and training for all crew, addressing the increased risk of crews with no Arctic experience, and increasing the requirements for officer navigational certification. The high life-safety consequence severity posed by fishing vessels needs to be recognized. Inclusion of fishing vessels under the Polar Code may mitigate the life-safety risk in the Arctic fishing industry

Recommendations for future work include refinement of evacuation scenarios and factors, including the potential integration of the life-safety consequence model with existing models for Arctic response time. More holistic risk-based decision-making for Arctic marine policy and operations requires further research to expand the existing consequence model to include environmental impacts of Arctic shipping. There remains a need for continued collection and analysis of Arctic ship accident data to support Arctic risk assessments and mitigation.

3.8. Acknowledgements

The financial support of the Lloyd's Register Foundation is acknowledged with gratitude. Lloyd's Register Foundation helps to protect life and property by supporting engineering-related education, public engagement and the application of research (grant number GA\100077).

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4. A CONSEQUENCE AGGREGATION METHOD FOR ARCTIC SHIP ACCIDENTS

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4.2. Abstract

Risk aggregation is the process of combining multiple individual risks to develop a better understanding of the overall risk on a system. Multiple risks can result from a single hazard impacting a system in different ways, or from different unique hazards. Different risks can have different consequences and different units of measure. This study investigates the aggregation of risk characterizations, specifically, different types of consequences posed by an Arctic ship accident. A general consequence aggregation method is presented,

considering ecological and socio-economic consequences of a potential oil spill, and life-safety consequences of a potential ship evacuation. Existing models for each consequence type are adopted. Individual consequence types are monetized and aggregated to quantify total consequence cost for a given accident scenario. A framework is proposed to assign a qualitative rating for total consequence severity. The qualitative scales of the framework are established using the quantitative aggregation method. Total consequence severity is evaluated for different ship types and regions in the Canadian Arctic. Results indicate that Arctic ship accidents involving oil tankers in environmentally sensitive regions and cruise ships in regions associated with long response times are worst-case scenarios, with similar total consequence severity levels. Implications for safe Arctic shipping are that mitigating the risks associated with Arctic cruise operations is of equal priority to that of Arctic tanker operations. The consequence aggregation method provides decision-makers and risk analysts with a data-driven tool to integrate multidisciplinary knowledge for the assessment, management, and communication of Arctic shipping risks.

4.3. Introduction

Risk aggregation is the process of summing multiple individual risks to gain a better understanding of the overall risk to a system. While risk aggregation as a concept is common in risk management practices, the concept is used in different ways with a range of risk perspectives [1].

Risk can be characterized as the combination of the consequences of an activity and the associated uncertainty [2]. Bjørnsen & Aven [1] distinguish between characterizing aggregate risks and aggregating risk characterizations.

Characterizing aggregate risks refers to the assignment of single measures of consequence and uncertainty for multiple risks. Aggregating risk characterizations refers to the aggregation of multiple individual risk characterizations (i.e. separate combinations of consequence and uncertainty). For the aggregation of risk characterizations, individual consequences are aggregated while the associated uncertainty is typically expressed as a single measure.

The current study focuses on the aggregation of consequences of Arctic ship accidents, contributing to the aggregation of risk characterizations. Estimating the associated uncertainty is out of scope for the current study.

Arctic maritime operations are complex socio-technical systems exposed to multiple risks [3-6]. A ship accident in the Arctic poses potential consequences to the vessel, crew and passengers, environment, local communities, and other Arctic stakeholders [3,7-9].

An oil spill in Arctic waters poses the potential for severe ecological and socio-economic consequences [10,11]. A ship evacuation in Arctic waters poses the potential for severe life-safety consequences to crew and passengers [7]. There is a need for increased emergency response preparedness for ship accidents in the Arctic [12].

The holistic management of safe ship operations requires consideration of multiple risk perspectives. There are competing interests among Arctic stakeholders with respect to the promotion of the Arctic maritime industry and the mitigation of associated risks. Some stakeholders favour increasing ship activity and development of Arctic regions in order to realize the associated economic benefits. Others advocate for protection of the Arctic environment and communities [10].

Evaluating the aggregated consequence severity of potential ship accidents in Arctic waters contributes to evidence-based decision-making for safe ship operations, Arctic maritime governance, emergency response planning, and environmental protection.

The contribution of this paper is a general method to aggregate consequences posed by an Arctic ship accident. The aggregation method is presented in two forms. A quantitative method is presented in which the aggregated consequence severity is estimated as a total consequence cost. Following this, a framework is proposed to qualitatively rate total consequence severity.

The quantitative method adopts existing models for ecological and socio-economic consequences of Arctic oil spills [13], and life-safety consequence of Arctic ship evacuations [7]. Consequence aggregation is achieved through monetization and summing of individual consequence costs. The aggregated consequence severity is estimated as the total consequence cost for a given accident scenario.

To support the assessment, management, and communication of Arctic shipping risks, a framework to qualitatively rate total consequence severity is proposed. The framework uses predefined matrices to evaluate and aggregate qualitative categories for environmental (i.e. ecological and socio-economic) and life-safety consequence, based on ship type and geographic region. The qualitative categories of the framework are defined based on the quantitative consequence aggregation method.

The total consequence severity of Arctic ship accidents is evaluated for different ship types and regions of the Canadian Arctic.

The remainder of this section introduces the concept of risk aggregation, approaches for evaluating environmental consequences of oil spills and life-safety consequences of ship evacuations in Arctic waters, and the valuation of maritime oil spills and fatalities.

4.3.1. Risk aggregation

Risk aggregation is a common practice used to gain an understanding of a more complete risk picture, improving risk management and communication [1,14].

Multiple definitions and applications of risk aggregation exist in the literature. Discussions on the concept of risk aggregation and reviews of various ways in which it is defined and performed are provided by Bjørnsen & Aven [1] and David [14].

This section provides a review of approaches for risk aggregation, highlighting several Arctic maritime applications. The relation to integrated risk management is discussed.

Consequence and uncertainty are characterizations of risk [2]. Bjørnsen & Aven [1] distinguish between characterizing aggregate risks and aggregating risk characterizations.

Characterizing aggregate risks refers to single measures for the consequence and uncertainty associated with the realization of multiple separate activities. The multiple separate activities are effectively treated as a single risk.

Aggregating risk characterizations refers to the combining of individual measures of consequence for multiple separate activities. The uncertainty associated with the multiple activities is expressed as a single measure. The strength of knowledge informing risk characterizations may also be considered in the aggregation process. The current study focuses on the aggregation of consequences.

One approach to aggregate consequences is to monetize individual consequence types. Afenyo et al. [13] aggregate socio-economic consequences of an oil spill in the Canadian Arctic through the summation of individual monetized consequence values. Leva et al. [15] use monetization to aggregate different consequence types across business units of a company. The aggregated consequence supports prioritization of company-wide risk control options.

Several studies incorporate risk matrices in the risk aggregation process. Using a combination of risk matrices and Bayesian Networks (BN), the risks of damage and besetting for ships navigating in ice are aggregated. Individual risks are assessed using matrices [16]. Risk matrix information is transferred to conditional probability tables and the total aggregated risk is estimated through the BN.

Three methods to aggregate risk matrices and quantitatively express qualitative risk ratings are proposed by Bao et al. [17]: fuzzy sets, interval numbers, and probability density functions. The quantitative expressions are aggregated and then transformed back to discrete risk values.

While risk matrices are a popular means to categorize and rank risks [18], there is an inherent ambiguity associated with risk matrices [15,17,18]. When qualitative categories of risk matrices are defined by an underlying quantitative relation, the qualitative and quantitative comparison of two risks may not align, e.g. one risk may receive a higher qualitative rating than a second risk, but is evaluated to have a lower quantitative value.

Integrated risk assessment and multi-risk assessment share similarities with risk aggregation, yet are distinct concepts.

An example of integrated risk management in Arctic shipping is the Integrated Arctic Corridors Framework [8]. The framework promotes safe Arctic shipping in Canada by defining safe shipping corridors through consideration of environmental features and Inuit rights.

Outside of the maritime industry, the World Health Organization provides a general framework for integrated risk assessment for risks posed to humans, ecology, and natural resources from chemical exposures [19]. The European Commission provides guidance on multi-risk assessment for hazard interactions during disaster management [20].

Integrated and multi-risk risk assessment support the consolidation of risk information, but they do not provide structured methods to aggregate risk.

4.3.2. Environmental consequence of Arctic oil spills

This section provides an overview of environmental consequences of Arctic oil spills. Existing approaches for evaluating ecological and socio-economic consequences are introduced. Methods employing consequence aggregation are highlighted.

The prevention of an oil spill, particularly in ice-covered waters, has been considered the highest priority for protection of the Arctic environment [9]. Environmental consequences of an oil spill include impacts to species and habitats (i.e. ecological consequences) [11,21] and stakeholder use of the Arctic (i.e. socio-economic consequences) [8-10,13].

Evaluating the impact of an Arctic oil spill is challenging. The environmental consequences are complex and poorly understood [11] and there is no definite strategy for evaluation [10].

A probabilistic evaluation of socio-economic consequences of an oil spill in the Canadian Arctic is presented by Afenyo et al. [10]. The method combines a multi-period consequence model with Bayesian Networks to evaluate cumulative effects over time. Indigenous socio-economic indicators specific to the Canadian Arctic are modelled. Multiple consequence types are aggregated by monetizing consequence severities and summing the costs.

Studies have focused on acute, short-term ecological impacts to individual species [11] and ecosystem functional groups (e.g. apex predators, bottom feeding mammals) [21].

A probabilistic method to quantify species-specific ecological consequences of an Arctic oil spill is presented by Helle et al. [11]. Consequence severity is assessed as the proportion of a given population that dies within two weeks of the spill. Nevalainen et al. [21] propose an ecosystem food web based model. Consequence severity is assessed as the percentage decrease in population of an ecosystem functional group.

These studies provide valuable information on ecological impacts of Arctic oil spills, but they do not provide a means to aggregate consequence severities for different species or functional groups.

Several studies propose the use of sensitivity as a proxy for ecological and socio-economic consequence severity [13,22-27].

The conservation value of threatened species and habitats in the northern Baltic Sea is used as a proxy for ecological consequence severity of oil spills [25]. Individual conservation values are aggregated by summation. The total ecological risk is the product of the probability for oil to be present and the aggregated conservation value.

Santos et al. [23] estimate the vulnerability of a region to oil spills using ecological and socio-economic indicators. Individual indicator values are aggregated to estimate total vulnerability.

The methodologies discussed thus far support species- and region-specific evaluations. Several studies evaluate environmental consequence of oil spills on a more global scale. The concept of sensitivity as a proxy for consequence severity is often employed.

An Arctic Council report evaluates areas of heightened ecological significance across the entire Arctic [28]. The assessment considers the sensitivity of fauna to oil spills and ship disturbances. An attempt was made to establish areas of heightened cultural significance but was not completed due to a lack of data.

The environmental sensitivity and risk to oil spills for the Canadian Arctic is evaluated using an Environmental Sensitivity Index (ESI) [13]. The Canadian Arctic is partitioned into eighteen zones and an ESI is calculated for each zone.

The ESI value captures ecological and socio-economic factors. Three indicators are calculated for physical sensitivity (e.g. data on shoreline type, ice coverage), biological resource (e.g. data on ecological and biological significant areas), and human-use resource (e.g. data on coastal population, tourism, freight tonnage). The ESI value is estimated by a weighted summation of the three indicator values. Similar analyses have been completed for non-Arctic Canadian waters [24,26].

ESI values for the Canadian Arctic [13] are adopted for the current study, representing the environmental (i.e. ecological and socio-economic) sensitivity of a region to an oil spill.

4.3.3. Life-safety consequence of Arctic ship evacuations

This section introduces definitions for life-safety risk and consequence severity in the maritime industry. An overview of studies supporting the evaluation of life-safety consequence of Arctic ship evacuations is provided.

The International Maritime Organization (IMO) revised guidelines for Formal Safety Assessment (FSA) [29] define life-safety risk as an area of risk concerning the level of harm to humans, considering illness, injury, and death. Life-safety consequence severity is typically expressed as an expected number of equivalent fatalities. Injuries are linked to fatalities using equivalence ratios: 10 minor injuries equates to 1 severe injury, and 10 severe injuries equates to 1 fatality.

A five-point index for life-safety consequence severity is defined by the IMO (Table 4.1). Severity indices correspond to orders of magnitude of equivalent fatalities.

Table 4.1. Life-safety consequence severity index (originally presented by Browne et al. [7], modified from the IMO FSA guidelines [29]).

Severity index	Severity	Effects on human safety	Equivalent fatalities
1	Minor	Single or minor injuries	0.01
2	Severe	Multiple or severe injuries	0.1
3	Significant	Single fatality or multiple severe injuries	1
4	Catastrophic	Multiple fatalities	10
5	Disastrous	Large number of fatalities	100

Ship evacuations in Arctic waters expose crew and passengers to a number of challenges and the potential for loss of life. Remote regions and a lack of search and rescue (SAR) infrastructure can lead to increased emergency response times. Life-saving appliances may be inadequate to support survival for longer response times. The presence of sea ice can impede launch of survival craft. [7,12,30].

A number of studies investigate Arctic shipping risk based on historical accident data. Studies have analyzed data across the entire Arctic [9,31-34], while other studies have focused on specific regions, e.g. Canada [35,36], Russia [37,38], and the Atlantic Arctic [12].

Studies have also investigated factors influencing the potential for loss of life during Arctic ship evacuations. Factors include SAR capabilities and capacities [12,39,40], performance of life-saving appliances [41], and emergency response times [42-44]. Response time estimates throughout the Canadian Arctic were proposed by Kennedy et al. [42].

The SARex exercises were a large scale initiative evaluating procedures for escape, evacuation, rescue, and survival under Arctic conditions [45-47].

These studies provide insight into accident frequencies and risk factors, but the data are insufficient to support an evaluation of life-safety consequence severity.

The SAFEDOR project evaluates the life-safety risk for different accident scenarios and ship types [48-50]. Life-safety consequence severity is measured as an expected number of fatalities, estimated as a percentage of the total number of persons on board (POB). The study is not specific to Arctic shipping.

Specific to Arctic maritime operations, Browne et al. [7] establish a life-safety consequence model for Arctic ship evacuations using expert knowledge. The consequence model consists of a qualitative conceptual framework of the factors influencing consequence severity, and quantified severities for a range of evacuation scenarios.

Evacuation scenarios consider ship type, the number of POB, and combinations of response time, season, ice conditions, metocean conditions, and time available to evacuate. Response time is identified as the most significant factor influencing the consequence severity of an Arctic ship evacuation. Among ship types, the evacuation of high POB passenger vessels, e.g. cruise ships, pose a particularly high life-safety consequence severity.

The current study adopts and combines the life-safety consequence severity model developed by Browne et al. [7] and the response time estimates established by Kennedy et al. [42].

4.3.4. Valuation of consequences

The valuation of maritime oil spills and fatalities are discussed in this section.

4.3.4.1. Valuation of maritime oil spills

The total cost of an oil spill is often separated into clean-up costs, environmental damage, and socio-economic costs [29,51,52]. At a more granular level, costs can be associated with asset damage, containment, clean-up, lost oil, lost income to businesses, lost consumer value, natural resource damage, and litigation for the party responsible for the spill as well as government and stakeholders impacted by the spill [53].

The cost of an oil spill is influenced by the type of oil, the location of the spill, characteristics of the region, spill volume, and the efficacy of response operations [52]. Despite the complexities of oil spills and the associated costs, cost estimates are often simplified to a function of spill volume [29,51,52].

An estimate for the total cost of an oil spill from ships is provided in the IMO Formal Safety Assessment (FSA) guidelines [29] (Eq. 4.1). The total spill cost reflects clean-up operations, property damage, economic losses, environmental damage, and legal costs [51]. The estimate is a global average based on consolidated data from the International Oil Pollution Compensation Fund (IOPCF), the US, and Norway.

$$global\ average\ spill\ cost = 67{,}275V^{0.5893} \tag{4.1}$$

where V is spill volume in tonnes, and spill cost is in US dollars (USD).

Average oil spill clean-up costs by region were published through the SAFEDOR project [52]. A significant regional variation is observed, ranging from a minimum of 1,300 USD per tonne in the Middle East to a maximum of 33,300 USD per tonne in Asia. The global average is 15,900 USD per tonne, while the North American average is 24,000 USD per tonne.

Oil spill cost data from the IOPCF [51] and the SAFEDOR project [52] suggest that environmental damage and socio-economic costs of a spill are approximately 1.5 times the clean-up cost, or 60% of the total spill cost.

Based on the clean-up cost data from the SAFEDOR project, total spill cost, as a global average and for North America, is estimated at 39,750 and 60,000 USD per tonne, respectively.

For comparison, the total spill cost estimates proposed in the IMO FSA [29] and the SAFEDOR project [52] are plotted in Figure 4.1.

The IMO FSA total spill cost function models a decrease in cost per tonne with increasing spill volume. The SAFEDOR project models a linear relationship between spill volume and cost. This explains the increasing discrepancy between the estimates with increasing spill volume.

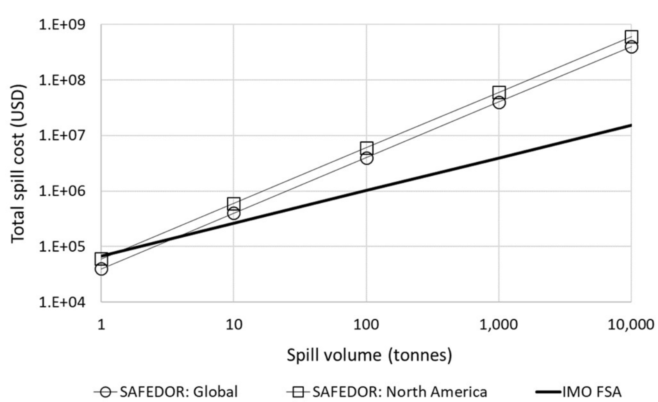

Figure 4.1. Comparison of IMO FSA [29] and SAFEDOR [52] total spill cost estimates.

Alternative methods for the valuation of Arctic oil spills are proposed in the research literature. The socio-economic impacts of an Arctic oil spill are estimated through summation of defined cost functions for environmental damage, economic impacts, and clean-up [54].

Afenyo et al. [10] propose a multi-period model for the socio-economic cost of an oil spill over time in the Canadian Arctic. The model considers unit costs for socio-economic factors, including psychological distress and crime on a per capita basis, and the compensation amounts stipulated in indigenous lands claim agreements.

Contingent valuation studies assess the public's willingness to pay (WTP) for oil spill risk mitigation measures. Noring et al. [55] assess the value of ecosystem services (e.g. habitat, biodiversity, recreation) at risk to oil spills in the Norwegian Arctic. Carson et al. [56] assess the WTP in the US to prevent another oil spill in the Arctic with the same spill volume as the 1989 Exxon Valdez accident.

While WTP estimates provide an indication of the public's perception of the economic importance of risk reduction, they do not provide an estimate of total cost.

For the valuation of an Arctic oil spill, the current study adopts the IMO FSA estimate for total spill cost (Eq. 4.1). The estimate is modified to reflect the increased sensitivity of Arctic regions. Full details are provided in Section 4.4.

4.3.4.2. Valuation of maritime fatalities

In risk management, the cost of a fatality is established for the purpose of evaluating cost-effectiveness of risk control options. A common measure is the cost of averting a fatality (CAF), also referred to as the value of a statistical life (VSL).

The CAF is the ratio of the additional cost of a risk control option to the reduction in risk in terms of fatalities averted. CAF values have been established through contingent valuation studies, historical data on risk mitigating measures, and societal indicators, such as life quality indices [29,57].

A range of CAF values have been established for different countries, industries, and organizations. The SAFEDOR project provides a summary of such valuations [52]. In the US, the Federal Aviation Industry and the Department of Transportation suggest 3 million USD, the Occupational Safety and Health Administration suggests 3.5 million USD, and the Environmental Protection Agency suggests 6 million USD. Offshore energy companies adopt values as high as 9 million USD. In Canada, CAF estimates have ranged from 1 to 3 million USD.

The IMO FSA guidelines adopt a CAF value of 3 million USD for use in the maritime industry [29]. This value is considered appropriate when equivalent fatality estimates include the risk of illness and injury.

A CAF of 3 million USD is adopted as the cost of a fatality for the current study.

4.4. Method

A general method to aggregate consequences posed by Arctic ship accidents is presented in this section. The method is presented in two forms. A quantitative method estimates total consequence severity as a total consequence cost (Section 4.4.1). A framework is proposed to qualitatively rate total consequence severity (Section 4.4.2). The quantitative and qualitative methods are illustrated using two ship accident scenarios.

4.4.1. Quantitative consequence aggregation method

Potential ecological and socio-economic consequences of an oil spill, and life-safety consequences of a ship evacuation, are aggregated to estimate total consequence severity. Individual consequence severities are evaluated, monetized, and aggregated by summation to estimate the total consequence cost of an Arctic ship accident scenario.

Five existing models are adopted for the evaluation and monetization of consequence severity. Adopted models and their application in the current study are summarized in Table 4.2.

Table 4.2. Summary of existing models adopted for consequence aggregation of Arctic ship accidents.

Model	Original source	Application
Spill volume class	Dillon [24]	Ecological & socio-economic consequence
Environmental Sensitivity Index (ESI)	WSP [13]	
Life-safety consequence severity index function	Browne et al. [7]	Life-safety consequence
Response time estimates	Kennedy et al. [42]	
Valuation of maritime oil spills & fatalities	IMO FSA [29]	Monetization

The process for calculating total consequence cost of an Arctic ship accident scenario is presented in Figure 4.2. The process is described in the following sections.

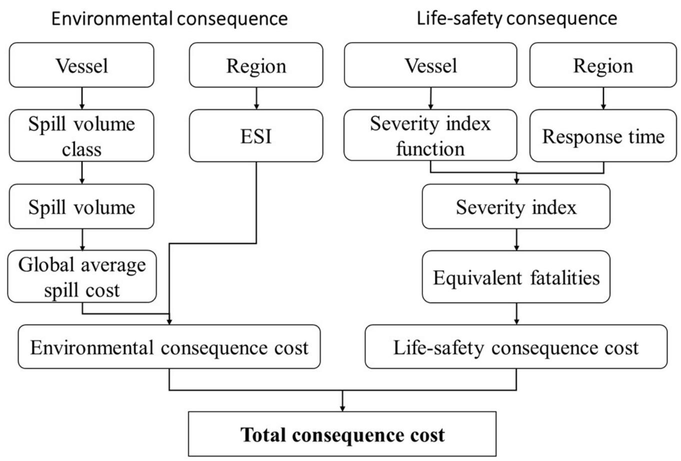

Figure 4.2. Process for calculating total consequence cost of an Arctic ship accident scenario.

4.4.1.1. Environmental consequence

The process for calculating environmental consequence cost for an oil spill in Arctic waters is depicted on the left-hand side of Figure 4.2.

The environmental consequence model is based on the vessel and region of an Arctic ship accident scenario. The vessel is assigned a spill volume class which provides an indication of the expected spill volume. A global average spill cost is estimated as a function of spill volume. The environmental sensitivity of the region to oil is modelled using an ESI, which reflects ecological and socio-economic impacts. The environmental consequence cost is estimated as the product of global average spill cost and the ESI value.

4.4.1.1.1. Spill volume class

Spill volume classes originally derived for the assessment of oil spill risks in Canadian waters [24] are adopted for the current study.

Spill volume class associates an expected spill volume range with typical ship types. Minimum and maximum expected oil spill volumes have been established through statistical analysis of ship accident data, considering, amongst other things, accident and spill occurrence frequencies and typical locations and capacities of fuel and cargo oil tanks.

Average oil spill volumes are adopted for the current study. Spill volume classes and average spill volumes for typical ship types are presented in Table 4.3.

Table 4.3. Spill volume classes (modified from the Transport Canada Area Risk Assessment [24]).

Spill volume class	Average spill volume (tonnes)	Typical ship type
1	14	Fishing, Recreation
2	81	Small commercial
3	512	Medium commercial
4	2,670	General purpose, Med. range tanker
5	8,900	Long range tanker, Panamax
6	20,025	Aframax
7	57,850	New Panamax, Suezmax
8	> 89,000	Very and Ultra Large Crude Carriers

4.4.1.1.2. Environmental Sensitivity Index

The ecological and socio-economic sensitivity of a region to oil is evaluated using an Environmental Sensitivity Index (ESI). The ESI method was originally developed for assessment of marine oil spill risk in Australia [27]. The method was later adapted and applied to the Canadian Arctic [13].

ESI values are estimated by a weighted summation of three indicator values: Physical Sensitivity Indicator (PSI), Biological Resource Indicator (BRI), and Human-use Resource Indicator (HRI).

PSI accounts for the difficulty of shoreline clean-up operations, considering, e.g. presence of ice along shorelines and shoreline length. BRI accounts for the sensitivity of natural resources to oil, considering, e.g. protected areas, species at risk, and biological functions of marine fauna. HRI accounts for commercial losses and impacts to social resources and human activities, considering, e.g. coastal population, tourism, and national and international freight tonnage.

The Canadian Arctic is partitioned into eighteen zones and ESI values established for each zone [13]. ESI values for the Canadian Arctic are evaluated using a five-point relative index, from 1 (very low) to 5 (very high). The eighteen zones and associated ESI ratings are presented in Appendix C.

The underlying quantitative scale for ESI value was not presented [13]. For the purpose of this study, the ESI value is assumed to follow a geometric progression, as per Table 4.4.

Justification for the assumption of a geometric progression is that the Transport Canada Area Risk Assessment established a similar index following the original ESI method [24,27]. The index is referred to as a Consequence of Exposure (COE) and estimates the sensitivity of non-Arctic Canadian waters to oil. The five-point COE index follows a geometric progression.

Table 4.4. ESI ratings, sensitivity descriptions, and ESI values (modified from WSP [13]).

ESI	Relative sensitivity description	ESI value
1	Very low	1
2	Low	2
3	Medium	4
4	High	8
5	Very high	16

4.4.1.1.3. Environmental consequence cost

Environmental consequence severity of an oil spill is estimated by an environmental consequence cost. The IMO global average spill cost function [29] (Eq. 4.1) is adopted for the current study. Global average spill cost is estimated as a function of the average spill volume. To account for the sensitivity of Arctic regions, the global average spill cost is multiplied by the regional ESI value (Eq. 4.2). Costs are in USD.

$$environmental\ consequence\ cost = global\ average\ spill\ cost \times ESI\ value \tag{4.2}$$

4.4.1.2. Life-safety consequence

The process for calculating life-safety consequence cost for a ship evacuation in Arctic waters is depicted on the right-hand side of Figure 4.2.

The life-safety consequence model is based on the vessel and region of an Arctic ship accident scenario. The vessel has an associated life-safety consequence severity index function. An expected response time for the region is estimated. The severity index is calculated as a function of response time, and equates to an expected number of equivalent fatalities. The life-safety consequence cost is estimated based on the number of equivalent fatalities and the CAF.

4.4.1.2.1. Severity index function

Life-safety consequence severity index functions for different ship types are established based on the consequence model developed by Browne et al. [7]. Arctic shipping experts rated consequence severity for Arctic ship evacuation scenarios using the five-point index defined in Table 4.1. Average consequence severity index values (decimal values) were estimated as the mean of the expert ratings.

Response time was identified as having the greatest influence on consequence severity. Four evacuation scenarios tested the effect of response time on consequence severity. Selected response times were 12, 24, 48, and 120 hours. All other evacuation scenario factors were held constant: summer, sea ice present, calm metocean conditions, and a controlled evacuation (i.e. time available for evacuees to don PPE and board and launch survival crafts).

Average consequence severity index values for five ship types and POB for the four response times are presented in Table 4.5.

Table 4.5. Average life-safety consequence severity index values for different response times (modified from Browne et al. [7]).

Ship type	POB	Response time (hrs)			
		12	24	48	120
Fishing	10	1.8	2.1	2.9	3.4
Pleasure	10	1.6	2.1	2.7	3.3
Cargo	25	1.5	1.9	2.6	3.4
Passenger	250	1.9	2.4	3.1	3.9
Passenger	1000	2.6	2.9	3.6	4.4

For the current study, severity index functions for each ship type are established through regression analysis with the data in Table 4.5. The equations estimate life-safety consequence severity index value SI as a function of response time t. Severity index functions (Eq. 4.3 to 4.7) with coefficients of determination R^2 are presented in Table 4.6.

Table 4.6. Severity index functions for defined ship types and POB.

Ship type	**POB**	**Severity index function**	R^2	**Eq.**
Fishing	10	$SI = 0.72\ln(t) - 0.04$	0.98	(4.3)
Pleasure	10	$SI = 0.74\ln(t) - 0.21$	0.99	(4.4)
Cargo	25	$SI = 0.86\ln(t) - 0.74$	0.99	(4.5)
Passenger	250	$SI = 0.86\ln(t) - 0.26$	0.99	(4.6)
Passenger	1000	$SI = 0.80\ln(t) + 0.51$	0.98	(4.7)

4.4.1.2.2. Response time

Response time estimates established by Kennedy et al. [42] are adopted for the current study. Response times for eight locations throughout the Canadian Arctic are estimated through an expert knowledge elicitation study. Response time estimates assume a ship evacuation with 18 POB in the summer and all POB successfully evacuate in survival craft.

Two response time estimates are established for each location, assuming an emergency response with 1) an air-based SAR asset (i.e. a helicopter), and 2) a marine-based SAR asset (i.e. a vessel). Minimum and maximum response times (i.e. best- and worst-case scenarios) for each location and SAR asset scenario were estimated.

Average response times are adopted for the current study. Average response times for each location and SAR asset scenario are presented in Table 4.7.

Table 4.7. Average response time estimates by location (modified from Kennedy et al. [42]).

Location	**Lat.**	**Long.**	**Average response time (hrs)**	
			Air asset	**Marine asset**
Amundsen Gulf	70.79	-125.51	20.5	89.5
Coronation Gulf	68.12	-112.63	19.0	44.5
Viscount Melville Sound	74.28	-102.63	32.5	31.0
Bathurst Island (North)	77.12	-98.53	34.5	144.5
Greely Fjord	80.56	-81.14	38.0	142.5
Lancaster Sound	74.10	-80.64	23.5	19.0
Foxe Basin	67.11	-78.41	21.5	88.0
Davis Strait	68.77	-65.08	19.5	33.5

Response time estimates assume an evacuation of 18 POB, which is the rescue capacity of a Cormorant helicopter. A marine-based SAR asset is assumed to have a much greater capacity [42].

For the purpose of this study, if the number of evacuees exceeds the capacity of a single SAR asset, deployment of multiple assets is assumed. It is acknowledged that the evacuation of a high POB passenger vessel may exceed the combined capacity of multiple SAR assets. In these scenarios, multiple trips between the accident location and a safe port would be required to rescue all evacuees.

Estimating the number and combination of SAR assets that would be deployed for a given evacuation scenario is beyond the scope of the current study. Piercey et al. [43] provide a model to estimate response time considering SAR capacity and the number of evacuees.

For low POB evacuations (i.e. fishing vessel, pleasure craft, and cargo vessel), the minimum average response time between air- and marine-based estimates is used for the calculation of life-safety consequence severity. For high POB passenger vessel evacuations, in which the number of evacuees exceeds the capacity of an air-based asset, marine-based response time estimates are used.

4.4.1.2.3. Life-safety consequence cost

Life-safety consequence severity of a ship evacuation is estimated by a life-safety consequence cost. The number of equivalent fatalities is estimated based on the logarithmic relation between the severity index SI and the order of magnitude of equivalent fatalities defined in Table 4.1 (Eq. 4.8).

$$equivalent\ fatalities = 10^{3-SI} \tag{4.8}$$

Life-safety consequence cost is estimated by multiplying the number of equivalent fatalities by the CAF (Eq. 4.9). A CAF of 3 million USD is recommended by the IMO [29] and adopted for the current study.

$$life\text{-}safety\ consequence\ cost = equivalent\ fatalities \times CAF \tag{4.9}$$

4.4.1.3. Total consequence cost

The aggregated consequence severity of a ship accident scenario is estimated by a total consequence cost. Total consequence cost is estimated by summation of the environmental and life-safety consequence costs (Eq. 4.10).

$$\begin{aligned} total\ consequence\ cost \\ &= environmental\ consequence\ cost \\ &+ life\text{-}safety\ conseqeunce\ cost \end{aligned} \tag{4.10}$$

4.4.1.4. Illustrative examples

Two ship accident scenarios are used to illustrate the quantitative consequence aggregation method: a cruise ship with 1000 POB in Bathurst Island (North), and an oil tanker with 25 POB in Lancaster Sound (Table 4.8).

Table 4.8. Quantitative results for illustrative ship accident scenarios.

Ship type	Cruise ship	Oil tanker
POB	1000	25
Region	Bathurst Is. (North)	Lancaster Sound
Spill volume class	4	5
Average oil spill volume (tonnes)	2,670	8,900
Global average spill cost (million USD)	7	14
ESI	1	4
ESI value	1	8
Environmental spill cost (million USD)	**7.0**	**114.4**
Response time	144.5	19
Severity index value	4.5	1.8
Equivalent fatalities	32.4	0.1
Life-safety consequence cost (million USD)	**97.2**	**0.2**
Total consequence cost (million USD)	**104.3**	**114.6**

The cruise ship is assigned spill volume class 4, with an average spill volume estimated at 2,670 tonnes. The global average spill cost, as a function of spill volume, is 7 million USD. The ESI for Bathurst Island (North) is 1 (Very Low), with an associated ESI value of 1. The environmental consequence cost is equal to the global average spill cost.

The life-safety consequence severity index function for a cruise ship with 1000 POB is presented in Eq. 4.7. A marine-based SAR response is assumed for high POB passenger vessels. The average marine-based response time for Bathurst Island (North) is 144.5 hours. The severity index value SI is estimated at 4.5, corresponding to 32.4 equivalent fatalities. Multiplying by the CAF (3 million USD), the life-safety consequence cost is estimated at 97 million USD.

The total consequence cost for a ship accident scenario with a 1000 POB cruise ship in Bathurst Island (North) is 104 million USD.

The oil tanker is assigned spill volume class 5, with an average spill volume of 8,900 tonnes. The global average spill cost is 14 million USD. The ESI for Lancaster Sound is 4, with an associated ESI value of 8. Multiplying the global average spill cost by the ESI value, the environmental consequence cost is 114 million USD.

For life-safety consequence modelling, the oil tanker is equivalent to a cargo vessel, and the severity index function is presented in Eq. 4.5. The minimum response time in Lancaster Sound is associated with a marine-based SAR response, at 19 hours. The severity index value is estimated at 1.8, corresponding to 0.1 equivalent fatalities. Multiplying by the CAF, the life-safety consequence cost is estimated at 0.2 million USD.

The total consequence cost for a ship accident scenario with a 25 POB oil tanker in Lancaster Sound is 115 million USD.

The cruise ship in Bathurst Island (North) poses a high life-safety consequence severity and a low environmental consequence severity. In contrast, the oil tanker in Lancaster Sound is dominated by a high environmental consequence severity, with a very low life-safety consequence severity. However, modelling the aggregated consequence demonstrates that the two vessels pose similar total consequence severities.

4.4.2. Qualitative consequence aggregation framework

In this section, a framework is proposed to qualitatively rate the total consequence severity of an Arctic ship accident scenario. The framework consists of matrices used to rate and aggregate individual consequence categories. The qualitative scales of the matrices are defined based on the quantitative consequence aggregation method.

A total consequence category is rated based on four factors: vessel spill volume class, regional ESI, vessel life-safety consequence severity index function, and regional response time estimate.

Spill volume class and ESI define the environmental consequence category. The life-safety consequence severity index function and response time define life-safety consequence category. The environmental and life-safety consequence categories define the total consequence category. The framework for evaluating the total consequence category is presented in Figure 4.3.

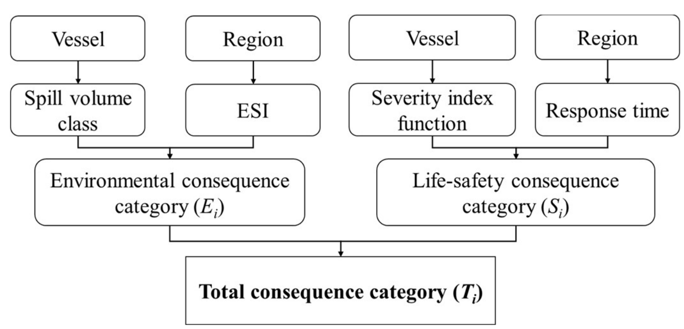

Figure 4.3. Framework for evaluating total consequence category.

4.4.2.1. Environmental consequence category

The environmental consequence category E_i for a ship accident scenario is determined by the vessel spill volume class and regional ESI.

Each spill volume class is defined by a minimum and maximum expected spill volume [24]. The associated range for global average spill cost is calculated using Eq. 4.1 and presented in Table 4.9.

Table 4.9. Spill volume class with minimum and maximum global average spill cost.

Spill volume class	**Global average spill cost (million USD)**	
	Min	**Max**
1	-	0.5
2	0.5	1.2
3	1.2	3.7
4	3.7	9.5
5	9.5	18.2
6	18.2	27.3
7	27.3	55.5
8	55.5	> 55.5

Multiplying by ESI value, the range for potential environmental consequence cost is determined for each combination of spill volume class and ESI.

For example, consider spill volume class 2 and ESI 4. The spill volume range is 27 to 134 tonnes, the global average spill cost range is 0.5 to 1.2 million USD, and multiplying by an ESI value of 8, the environmental consequence cost range is 3.7 to 9.6 million USD.

An environmental consequence cost matrix is established with vessel spill volume on the horizontal axis and ESI on the vertical axis (Figure 4.4). The value in each cell of the matrix is the maximum potential environmental consequence cost for the associated combination of spill volume class and ESI.

Environmental consequence cost (million USD)

ESI								
5	7.5	19.3	58.9	152.0	290.5	437.0	888.5	≥ 888.5
4	3.7	9.6	29.4	76.0	145.2	218.5	444.2	≥ 444.2
3	1.9	4.8	14.7	38.0	72.6	109.3	222.1	≥ 222.1
2	0.9	2.4	7.4	19.0	36.3	54.6	111.1	≥ 111.1
1	0.5	1.2	3.7	9.5	18.2	27.3	55.5	≥ 55.5
	1	2	3	4	5	6	7	8

Spill volume class

Figure 4.4. Environmental consequence cost matrix.

The qualitative environmental consequence category C_i is rated on a five-point index, based on the maximum potential environmental consequence cost for an accident scenario (i.e. spill volume class and ESI). Environmental consequence categories, severity descriptions, and cost ranges are defined in Table 4.10.

Table 4.10. Environmental consequence categories and cost ranges.

Environmental consequence category (E_i)	**Severity**	**Environmental consequence cost (million USD)**	
		Min	**Max**
E1	Very low	-	5
E2	Low	5	20
E3	Medium	20	80
E4	High	80	320
E5	Very high	320	≥ 320

The environmental consequence cost matrix is converted into a qualitative environmental consequence category matrix (Figure 4.5) using the environmental consequence category cost ranges. The environmental consequence category matrix allows for the qualitative rating of environmental consequence severity based on spill volume class and ESI.

Environmental consequence category

ESI								
5	E2	E2	E3	E4	E4	E5	E5	E5
4	E1	E2	E3	E3	E4	E4	E5	E5
3	E1	E1	E2	E3	E3	E4	E4	E5
2	E1	E1	E2	E2	E3	E3	E4	E4
1	E1	E1	E1	E2	E2	E3	E3	E4
	1	2	3	4	5	6	7	8

Spill volume class

Figure 4.5. Environmental consequence category matrix

Again, consider spill volume class 2 and ESI 4. The environmental consequence category is rated E2 (Low). E2 corresponds to a cost range of 5 to 20 million USD, which captures the maximum potential environmental consequence cost estimate of 9.6 million USD.

4.4.2.2. Life-safety consequence category

The life-safety consequence category S_i for a ship accident scenario is determined by the vessel's severity index function and the regional response time estimate.

Each life-safety consequence severity index is associated with an order of magnitude of equivalent fatalities. For the purpose of this study, the order of magnitude is assumed to correspond to a range of potential fatalities. Multiplying by the CAF, the range for life-safety consequence cost is determined.

For example, life-safety consequence category S2 has an order of magnitude of 1, corresponding to an equivalent fatality range of 1 to 9. Multiplying by the CAF, the consequence cost range is 3 to 27 million USD. To ensure continuity between the consequence cost ranges, the upper limit of the cost range is treated as 30 million USD.

Life-safety consequence categories, orders of magnitude of equivalent fatalities, and consequence cost ranges are presented in Table 4.11.

Table 4.11. Life-safety consequence categories and cost ranges.

Life-safety consequence category	**Severity**	**Equivalent fatalities (Order of magnitude)**	**Life-safety consequence cost (million USD)**	
			Min	**Max**
S1	Minor	0.01	-	0.3
S2	Severe	0.1	0.3	3
S3	Significant	1	3	30
S4	Catastrophic	10	30	300
S5	Disastrous	100	300	3,000

Note that under the quantitative method, the life-safety consequence severity index value is treated as a continuous variable, whereas the qualitative consequence categories are discrete. A calculated severity index value is round down to determine the consequence category, e.g. a severity index value of 3.9 corresponds to consequence category S3.

4.4.2.3. Total consequence category

The total consequence category T_i for a ship accident scenario is determined by the environmental and life-safety consequence categories.

Each environmental and life-safety consequence category has a range of potential consequence costs. The total consequence cost range for a combination of environmental and life-safety consequence categories is determined by summation of the respective minimum and maximum cost values.

For example, consider environmental and life-safety consequence categories of E2 and S4. The environmental consequence cost range is 5 to 20 million USD, the life-safety consequence cost range is 30 to 300 million USD, and by summation, the total consequence cost range is 35 to 320 million USD.

A total consequence cost matrix is established with environmental consequence category on the horizontal axis and life-safety consequence category on the vertical axis (Figure 4.6). The value in each cell of the matrix is the maximum potential total consequence cost for the associated combination of environmental and life-safety consequence categories.

Total consequence cost (million USD)

Life-safety consequence category	E1	E2	E3	E4	E5
S5	3005	3020	3080	3320	≥ 620
S4	305	320	380	620	≥ 350
S3	35	50	110	350	≥ 323
S2	8	23	83	323	≥ 320.3
S1	5.3	20.3	80.3	320.3	≥ 320

Environmental consequence category

Figure 4.6. Total consequence cost matrix.

The qualitative total consequence category T_i is rated on a five-point index, based on the maximum potential total consequence cost for an accident scenario (i.e. combination of environmental and life-safety consequence categories). Total consequence categories, severity descriptions, and cost ranges are defined in Table 4.12.

Table 4.12. Total consequence categories and cost ranges.

Total consequence category	**Severity**	**Total consequence cost (million USD)**	
		Min	**Max**
T1	Very low	-	<6
T2	Low	6	< 30
T3	Medium	30	< 150
T4	High	150	< 750
T5	Very high	750	≥ 750

The total consequence cost matrix is converted into a qualitative total consequence category matrix (Figure 4.7) using the total consequence category cost ranges. The total consequence category matrix allows for the qualitative rating of total consequence severity based on the environmental and life-safety consequence categories.

Total consequence category

Life-safety consequence category	E1	E2	E3	E4	E5
S5	T5	T5	T5	T5	T5
S4	T4	T4	T4	T4	T5
S3	T3	T3	T3	T4	T5
S2	T2	T2	T3	T4	T5
S1	T1	T2	T3	T4	T5

Environmental consequence category

Figure 4.7. Total consequence category matrix.

Again, consider environmental and life-safety consequence categories E2 and S4, respectively. The total consequence category is rated T4 (High). T4 corresponds to a cost range of 150 to 750 million USD, which captures the maximum potential total consequence cost estimate of 320 million USD.

4.4.2.4. Illustrative examples

The same ship accident scenarios are used to illustrate the qualitative consequence aggregation framework: a cruise ship with 1000 POB in Bathurst Island (North), and an oil tanker with 25 POB in Lancaster Sound. The two scenarios are evaluated and compared in Table 4.13.

The cruise ship is assigned spill volume class 4 and the ESI for Bathurst Island (North) is 1. The associated environmental consequence category is E2 (Low). A cruise ship with 1000 POB and a response time of 144.5 hours receives a severity index value of 4.5, corresponding to life-safety consequence category S4 (Catastrophic). The associated total consequence category is T4 (High).

The oil tanker is assigned spill volume class 5 and the ESI for Lancaster Sound is 4. The associated environmental consequence category is E4 (High). The life-safety consequence severity index value for a cargo vessel with 25 POB and a response time of 19 hours is 1.8, corresponding to the life-safety consequence category S1 (Minor). The associated total consequence category is T4 (High).

Similar results are obtained with the qualitative framework as with the quantitative aggregation method. The cruise ship in Bathurst Island (North) poses a potential catastrophic life-safety consequence severity and a low environmental consequence severity. The oil tanker poses a potential high environmental consequence severity and a minor life-safety consequence severity. Modelling the aggregated consequence demonstrates that both vessels pose the potential for high total consequence severities.

Table 4.13. Qualitative ratings for illustrative ship accident scenarios.

Ship type	Cruise ship	Oil tanker
POB	1000	25
Region	Bathurst Is. (North)	Lancaster Sound
Spill volume class	4	5
ESI	1	4
Environmental consequence category E_i	**E2**	**E4**
Response time	144.5	19.0
Severity index value	4.5	1.8
Life-safety consequence category S_i	**S4**	**S1**
Total consequence category T_i	**T4**	**T4**

4.5. Results

Results are presented for six combinations of ship type and POB at eight geographic locations throughout the Canadian Arctic. Thus, forty-eight accident scenarios are evaluated in total.

Combinations of ship type and POB correspond to those evaluated for life-safety consequence severity by Browne et al. [7] (see Table 4.5 and Table 4.6). For life-safety consequence, the bulk carrier and oil tanker are modelled as cargo vessels. Geographic locations correspond to those evaluated for response time by Kennedy et al. [42] (see Table 4.7). Geographic locations are mapped in Figure 4.8.

Results for the quantitative consequence aggregation method are presented in Section 4.5.1. Results for the qualitative consequence aggregation framework are presented in Section 4.5.2.

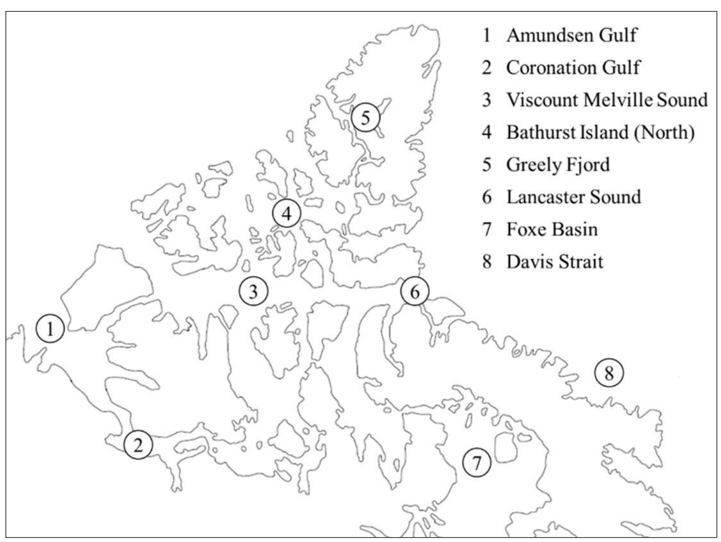

Figure 4.8. Canadian Arctic locations evaluated for total consequence severity (map modified from Natural Resources Canada [58]).

4.5.1. Quantitative consequence aggregation method

Total consequence costs are plotted in Figure 4.9. Locations are on the horizontal axis with the six ship types plotted for each location. Detailed quantitative results are tabulated in Appendix D.

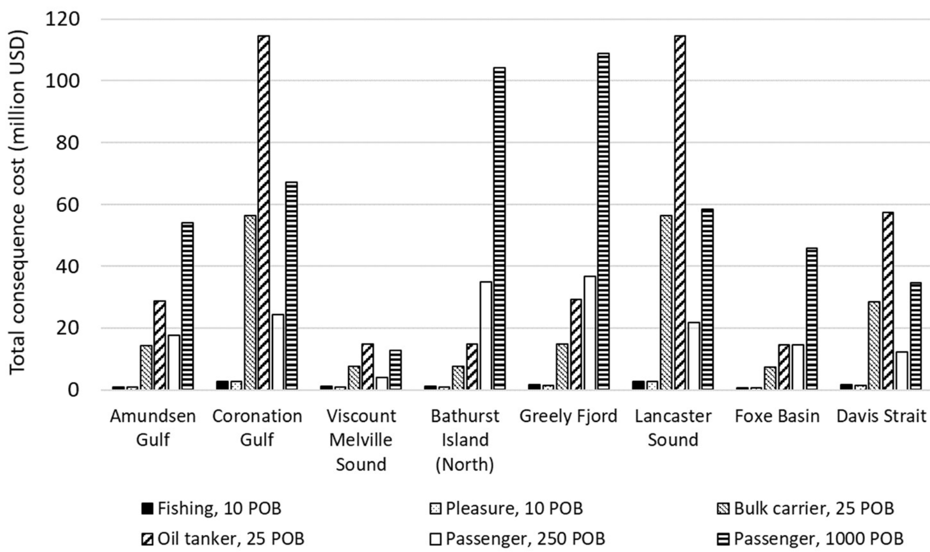

Figure 4.9. Total consequence cost by location for different ship types.

The highest total consequence cost scenarios are for the oil tanker with 25 POB in Coronation Gulf and Lancaster Sound, both estimated at 114.56 million USD. The next highest total consequence scenarios are for the 1000 POB passenger vessel in Greely Fjord and Bathurst Island (North), at 108.83 and 104.27 million USD, respectively.

Of the locations considered in the scenarios, Viscount Melville Sound is the location with the lowest average (of the six ship types) total consequence cost.

Among ship types, the fishing vessel and pleasure craft, each with 10 POB, are associated with the lowest total consequence cost estimates at all locations, ranging from 0.65 to 2.85 million USD.

The corresponding environmental and life-safety consequence costs are plotted in Figure 4.10 and Figure 4.11, respectively.

Environmental consequence cost is the predominant contributor to total consequence cost for the oil tanker and bulk carrier at all locations. Environmental consequence cost is determined, in part, by the modelled spill volume class and associated average spill volume. The oil tanker is modelled with spill volume class 5; the bulk carrier is modelled with spill volume class 4. These are the two highest spill volume classes modelled in the current study, and are thus associated with the highest environmental consequence cost at each location.

The 1000 POB passenger vessel is also modelled with spill volume class 4, resulting in the same environmental consequence cost estimates as the bulk carrier. However, the 1000 POB passenger vessel is associated with high life-safety consequence costs, resulting in total consequence costs above that of the bulk carrier. Similarly, but to a lesser extent, the total consequence costs for 250 POB passenger vessel are comprised of appreciable environmental and life-safety consequence costs.

Aside from the passenger vessels, all other ship types are estimated to have relatively low life-safety consequence costs at all locations, ranging from 0.19 to 1.18 million USD.

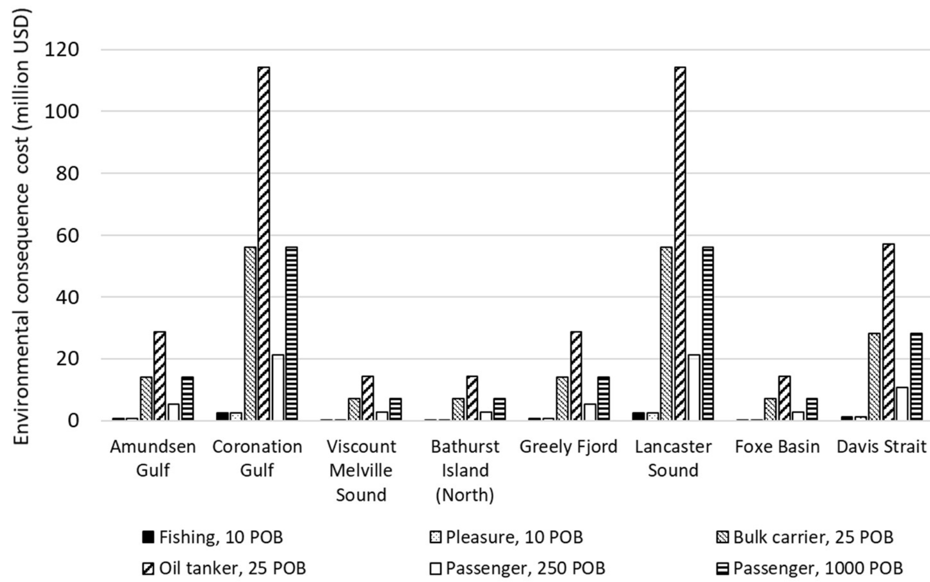

Figure 4.10. Environmental consequence cost by location for different ship types.

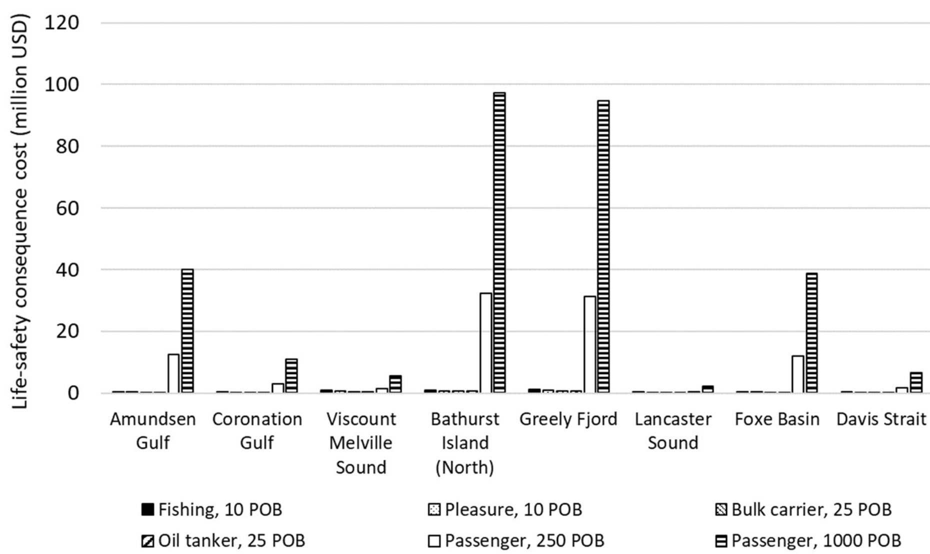

Figure 4.11. Life-safety consequence cost by location for different ship types.

4.5.2. Qualitative consequence aggregation framework

Results using the qualitative consequence aggregation framework are presented in Table 4.14 to Table 4.19. Each table is associated with a single ship type and POB combination.

Similar findings to the quantitative method are observed when comparing the qualitative ratings between ship types and locations. The oil tanker is rated with a total consequence category T4 (High) in Coronation Gulf and Lancaster Sound. The environmental consequence category is the predominant contributor at these locations, rated E4 (High).

Both the 1000 and 250 POB passenger vessels are rated with total consequence categories T4 (High) in Greely Fjord and Bathurst Island (North). The 1000 POB passenger vessel is also rated with a total consequence category T4 (High) in Amundsen Gulf and Foxe Basin.

The bulk carrier is rated with total consequence categories ranging from T2 (Low) to T3 (Medium) at all locations. The environmental consequence category is the predominant contributor, ranging from E2 (Low) to E3 (Medium). Note that the environmental consequence category ratings for the bulk carrier and the 1000 POB passenger vessel are equivalent at each location, as both are modelled with spill volume class 4.

The fishing vessel is rated with a total consequence category T2 (Low) at all locations. The pleasure craft is rated with total consequence categories ranging from T1 (Very Low) to T2 (Low). The predominant contributor to total consequence category rating for these ship types is the life-safety consequence category; both vessels are rated with an environmental consequence category of E1 (Very Low) at all locations.

Aside from the passenger vessels, all other ship types are rated with life-safety consequence severity categories ranging from S1 (Minor) to S2 (Severe).

Table 4.14. Qualitative consequence aggregation results by location; Fishing vessel, 10 POB.

Location	Spill volume class	ESI	Environmental conseq. cat.	Response time (hour)	Severity index value	Life-safety conseq. cat.	Total conseq. cat.
Amundsen G.	1	2	E1	20.5	2.15	S2	T2
Coronation G.	1	4	E1	19.0	2.09	S2	T2
VMS	1	1	E1	31.0	2.45	S2	T2
Bathurst I. (N)	1	1	E1	34.5	2.52	S2	T2
Greely Fjord	1	2	E1	38.0	2.59	S2	T2
Lancaster S.	1	4	E1	19.0	2.09	S2	T2
Foxe Basin	1	1	E1	21.5	2.18	S2	T2
Davis Strait	1	3	E1	19.5	2.11	S2	T2

Table 4.15. Qualitative consequence aggregation results by location; Pleasure craft, 10 POB.

Location	Spill volume class	ESI	Environmental conseq. cat.	Response time (hour)	Severity index value	Life-safety conseq. cat.	Total conseq. cat.
Amundsen G.	1	2	E1	20.5	2.02	S2	T2
Coronation G.	1	4	E1	19.0	1.97	S1	T1
VMS	1	1	E1	31.0	2.33	S2	T2
Bathurst I. (N)	1	1	E1	34.5	2.41	S2	T2
Greely Fjord	1	2	E1	38.0	2.48	S2	T2
Lancaster S.	1	4	E1	19.0	1.97	S1	T1
Foxe Basin	1	1	E1	21.5	2.06	S2	T2
Davis Strait	1	3	E1	19.5	1.99	S1	T1

Table 4.16. Qualitative consequence aggregation results by location; Bulk carrier, 25 POB.

Location	Spill volume class	ESI	Environmental conseq. cat.	Response time (hour)	Severity index value	Life-safety conseq. cat.	Total conseq. cat.
Amundsen G.	4	2	E2	20.5	1.86	S1	T2
Coronation G.	4	4	E3	19.0	1.80	S1	T3
VMS	4	1	E2	31.0	2.22	S2	T2
Bathurst I. (N)	4	1	E2	34.5	2.31	S2	T2
Greely Fjord	4	2	E2	38.0	2.39	S2	T2
Lancaster S.	4	4	E3	19.0	1.80	S1	T3
Foxe Basin	4	1	E2	21.5	1.90	S1	T2
Davis Strait	4	3	E3	19.5	1.82	S1	T3

Table 4.17. Qualitative consequence aggregation results by location; Oil tanker, 25 POB.

Location	Spill volume class	ESI	Environmental conseq. cat.	Response time (hour)	Severity index value	Life-safety conseq. cat.	Total conseq. cat.
Amundsen G.	5	2	E3	20.5	1.86	S1	T3
Coronation G.	5	4	E4	19.0	1.80	S1	T4
VMS	5	1	E2	31.0	2.22	S2	T2
Bathurst I. (N)	5	1	E2	34.5	2.31	S2	T2
Greely Fjord	5	2	E3	38.0	2.39	S2	T3
Lancaster S.	5	4	E4	19.0	1.80	S1	T4
Foxe Basin	5	1	E2	21.5	1.90	S1	T2
Davis Strait	5	3	E3	19.5	1.82	S1	T3

Table 4.18. Qualitative consequence aggregation results by location; Passenger vessel, 250 POB.

Location	Spill volume class	ESI	Environmental conseq. cat.	Response time (hour)	Severity index value	Life-safety conseq. cat.	Total conseq. cat.
Amundsen G.	3	2	E2	89.5	3.62	S3	T3
Coronation G.	3	4	E3	44.5	3.01	S3	T3
VMS	3	1	E1	31.0	2.70	S2	T2
Bathurst I. (N)	3	1	E1	144.5	4.03	S4	T4
Greely Fjord	3	2	E2	142.5	4.02	S4	T4
Lancaster S.	3	4	E3	19.0	2.28	S2	T3
Foxe Basin	3	1	E1	88.0	3.60	S3	T3
Davis Strait	3	3	E2	33.5	2.77	S2	T2

Table 4.19. Qualitative consequence aggregation results by location; Passenger vessel, 1000 POB.

Location	Spill volume class	ESI	Environmental conseq. cat.	Response time (hour)	Severity index value	Life-safety conseq. cat.	Total conseq. cat.
Amundsen G.	4	2	E2	89.5	4.13	S4	T4
Coronation G.	4	4	E3	44.5	3.56	S3	T3
VMS	4	1	E2	31.0	3.27	S3	T3
Bathurst I. (N)	4	1	E2	144.5	4.51	S4	T4
Greely Fjord	4	2	E2	142.5	4.50	S4	T4
Lancaster S.	4	4	E3	19.0	2.88	S2	T3
Foxe Basin	4	1	E2	88.0	4.11	S4	T4
Davis Strait	4	3	E3	33.5	3.34	S3	T3

4.5.3. Benchmark case study

A case study presented by Afenyo et al. [10] evaluates the socio-economic consequence cost of an oil spill in the Canadian Arctic. In this section, the case study cost estimate is used to benchmark the environmental consequence model developed for the current study.

The case study evaluates the multi-period socio-economic cost associated with an oil spill of 10.8 million barrels (approximately 37,000 tonnes) in Rankin Inlet. The oil spill volume is equivalent to that of the 1989 Exxon Valdez oil spill in Alaska. The cost estimate reflects a worst-case scenario in which no oil spill recovery or intervention takes place [10].

The multi-period model estimates consequence costs over time. A socio-economic consequence cost of 500 million USD is estimated for the first year following the oil spill. After five years, the socio-economic consequence cost grows to 7 billion USD.

The same oil spill scenario is examined using the environmental consequence model of the current study. Rankin Inlet has an ESI of 4 [13]. For an oil spill volume of 37,000 tonnes, the environmental consequence cost is estimated at 265 million USD. The environmental consequence category is rated E5 (Very High).

The environmental consequence cost estimate reflects clean-up costs, environmental damage, and socio-economic consequences. Environmental damage and socio-economic consequence costs are estimated to represent 60% of the total oil spill cost, i.e. clean-up costs account for the other 40% [29,52]. The cost associated with environmental damage and socio-economic consequence is thus estimated at 159 million USD, and is roughly one third the first year estimate by Afenyo et al. [10].

Several points warrant consideration when comparing the cost estimate of the current study against the benchmark case study.

Afenyo et al. [10] assume a worst-case scenario in which no oil spill recovery or intervention efforts take place. The environmental consequence model of the current study assumes clean-up operations take place.

Afenyo et al. [10] model consequence on a more localized scale, whereas the ESI used for the current study reflects a more global scale [13]. Further, different socio-economic indicators are used by each study. The ESI models socio-economic value using a Human-use Resource Indicator (HRI), which is quantified considering coastal population, tourism, and national and international shipping freight tonnage. Afenyo et al. [10] consider indigenous socio-economic indicators, such as the oil spill compensation stipulated in the region's indigenous land claims agreement, and costs associated with psychological distress and crime.

The current study estimates environmental consequence cost based on the IMO global average spill cost function [29]. The spill cost is based on a single value: spill volume. This is a practical approach but may not reflect the complexity of an oil spill and the associated environmental impacts. Further, 60% of the global average spill cost is estimated to be associated with environmental damage and socio-economic consequences. This proportion may not accurately represent the environmental consequence of an Arctic oil spill.

4.6. Discussion

4.6.1. Main findings

Total consequence severity of an Arctic ship accident is dependent on ship type and accident location. The consequence aggregation method allows for the total consequence severity of different ship accident scenarios to be evaluated and compared.

The worst-case accident scenario is an oil tanker in an environmentally sensitive region, e.g. Coronation Gulf or Lancaster Sound, or a high POB passenger vessel in a region associated with a long response time, e.g. Greely Fjord or Bathurst Island (North).

Accident scenarios in regions with lower environmental sensitivity, e.g. Viscount Melville Sound or Foxe Basin, and ship types with lower spill volume class, e.g. fishing vessels or pleasure craft, are associated with lower environmental consequence severity.

Accident scenarios in regions associated with shorter response times, e.g. Lancaster Sound or Viscount Melville Sound, and ship types with relatively low life-safety severity indices, e.g. cargo vessels, are associated with lower life-safety consequence severity.

Results for the quantitative consequence aggregation method are based on average values, providing a comparative indicator between potential ship accident scenarios. Environmental consequence costs are based on average spill volumes for a given spill volume class. Life-safety consequence costs are based on average response time estimates for a given region. The consequence severity realized from a ship accident in the Arctic will depend on the actual spill volume and response time.

The qualitative consequence aggregation framework captures the maximum potential consequence costs of a ship accident scenario. The qualitative framework rates consequence severities based on ranges of potential consequence costs. Environmental consequence categories consider the spill volume range associated with each spill volume class. The life-safety consequence categories consider the range of values encompassed by the order of magnitude of equivalent fatalities defined for each severity index.

There is a degree of ambiguity associated with the qualitative framework. For example, accident scenarios for a 1000 POB passenger vessel in Greely Fjord and Foxe Basin receive the same qualitative rating for total consequence category: T4 (High). The quantitative aggregation method distinguishes the two scenarios, estimating the total consequence cost in Greely Fjord to be 2.4 times greater than in Foxe Basin.

The issue of ambiguity is not unique to the current study. Ambiguity is inherent in all qualitative matrices established on the basis of an underlying quantitative relation [15,17,18]. Despite ambiguity, matrices remain a common and practical approach in risk management.

4.6.2. Implications for safe Arctic shipping and risk management

Evaluating the aggregated total consequence severity for Arctic ship accident scenarios allows for comparison of the overall risk exposure between ship types and operating regions.

The qualitative framework provides risk analysts and decision-makers with a systematic and coherent process for assessing, ranking, and communicating Arctic ship accident scenario severities. The framework uses pre-defined matrices established using the quantitative consequence aggregation method. As such, the results between the quantitative and qualitative methods are aligned.

Results suggest that an oil tanker accident in the Arctic is the worst-case scenario, due almost exclusively to the associated environmental consequence. High POB passenger vessels are associated with appreciable environmental and life-safety consequence severities. Aggregating consequence severities demonstrates that a high POB passenger vessel accident in the Arctic poses a comparable total consequence severity level to that of an oil tanker.

An oil spill has been recognized as the greatest threat facing the Arctic maritime environment [9]. The current study suggests that mitigating the risks associated with Arctic cruise operations is of near equal priority to that of Arctic tanker operations. Previous studies suggest the need for enhanced regulatory oversight of Arctic cruise operations [59].

Although Arctic ship operations pose risks to the environment and life-safety, they provide positive economic impacts to Arctic communities and stakeholders. Economic benefits must be considered in risk management of the Arctic maritime industry.

The Integrated Arctic Corridors Framework [8] is an example of balancing risk management and the realization of the benefits of Arctic shipping. The Integrated Arctic Corridors Initiative, a proposed expansion of the Canadian Coast Guard's Northern Marine Transportation Corridors Initiative, accounts for environmental features and Inuit rights in defining safe marine traffic corridors. Life-safety consequence is not considered.

While Arctic cruise operations pose a high total consequence severity, Arctic cruise operators are recognized for exercising operational risk management best practices. For example, cruise ships typically operate in close proximity with a support vessel when in remote regions. The recent voyages of the Crystal Serenity cruise ship through the Northwest Passage are recognized for having established a high standard for risk management and regulatory oversight [7].

The consequence severity of an Arctic ship accident will be impacted by the availability and capability of SAR services. The life-safety consequence severity of an Arctic ship evacuation has a strong dependence on emergency response time and capacity [7]. There is a need for the continued enhancement of, and international cooperation between, Arctic SAR services in order to decrease the consequence severity of Arctic ship accidents [45-

47,60]. This is particularly true for accident scenarios with high POB vessels which require the deployment and coordination of multiple SAR assets [39,40].

An operational risk management framework for Arctic ship navigation and voyage planning is proposed by Browne et al. [3]. The framework integrates ecological, socio-economic, and life-safety consequences into the Polar Operational Limit Assessment Risk Indexing System methodology [61]. The aggregated consequence level informs the assignment of operating criteria for ships in ice. Ships posing higher potential consequence severities are required to operate more conservatively. The consequence aggregation method developed for the current study supports the further development of the proposed operational risk management framework.

The current study focuses on the aggregation of risk characterizations, ultimately contributing to risk aggregation. Risk aggregation allows decision-makers to consider the total exposure to loss for a system, and supports holistic risk management [1,14].

It is important to consider if risk aggregation is suitable. Potential issues related to information loss and independence are highlighted by David [14]. While aggregated risk supports a better understanding of the complete risk picture and the context of individual risks, it should not replace the detailed information of single risks. The relation between individual risks must also be considered. Aggregating risks that are not independent may not be appropriate.

The consequence aggregation method proposed in the current study supports holistic data-driven risk management in the Arctic maritime industry. Decision-makers and risk analysts should consider the total consequence severity data together with the individual environmental and life-safety consequence data.

4.6.3. Future work

The environmental consequence severity of an Arctic oil spill is modelled as a function of the regional ESI for the accident location. Regional ESI values are modelled, in part, based on a HRI value which considers coastal population, tourism, and shipping freight tonnage for the region. The HRI is intended to reflect the socio-economic value of the region [13].

Socio-economic value in the Canadian Arctic should consider indigenous rights and land and marine uses. Several studies propose ways to capture indigenous values and consequence severities [8,10,62]. Expansion of the definition and calculation of regional ESI value to capture indigenous socio-economic impacts is necessary.

Life-safety consequence severity of an Arctic ship evacuation is a function of response time. Regional response time estimates assume the deployment of a single SAR asset. Multiple SAR assets may be deployed to an accident location. In the case of high POB evacuation, all available SAR assets, including nearby vessels of opportunity, may assist in the emergency response.

The number and combination of SAR assets will impact response time, and thus life-safety consequence severity. Studies have investigated the impact of SAR resource allocation and the presence of vessels of opportunity on response time [43,44], and may support the refinement of the life-safety consequence model.

In the Canadian Arctic, cruise ships are often escorted by an ice capable vessel as a risk mitigation strategy. The escort vessel provides icebreaking assistance and support in the event of an emergency. The use of vessel convoys is another risk mitigating practice. Future studies may investigate the potential efficacy of such approaches for reducing SAR response time and consequence severity.

The collection and analysis of Arctic ship accident case studies will contribute to the continued validation of consequence models and the valuation of oil spills and fatalities in Arctic waters.

The consequence aggregation method provides decision-makers and risk analysts with a tool for risk management in the Arctic maritime industry. Next steps include investigating how the consequence aggregation method supports existing efforts towards safe Arctic shipping and risk assessment [3,8,29].

Eliciting stakeholder feedback on the consequence aggregation method and the assignment of consequence category thresholds is an area for future work. Relevant stakeholders include seafarers, ship operators, insurance underwriters, policy makers, indigenous communities, and risk analysis practitioners.

4.7. Conclusion

A general consequence aggregation method for Arctic ship accidents is presented. Ecological, socio-economic, and life-safety consequences are considered. Existing models for each consequence type are adopted. Consequence aggregation is achieved through monetization of consequence severities.

The method includes the quantitative aggregation of total consequence cost, and a framework to assign a qualitative rating for total consequence severity. The qualitative consequence aggregation method provides risk analysts and decision-makers with a data-driven and practical procedure for assessing, managing, and communicating Arctic shipping risks.

The consequence aggregation method allows for the total consequence severity of different Arctic ship accident scenarios to be evaluated and compared. The total consequence severity of different ship accident scenarios throughout the Canadian Arctic are evaluated.

Results show that total consequence severity is dependent on ship type and accident location. Arctic ship accident scenarios involving oil tankers in environmentally sensitive regions, and high POB passenger vessels in regions associated with long response times, are worst-case scenarios.

While oil spills are recognized as the greatest threat facing the Arctic environment, the current study suggests that mitigating risks associated with Arctic cruise operations is of equal priority to that of Arctic tanker operations.

Recommendations for future work include the continued development of environmental and life-safety consequence models and validation of the consequence aggregation method. Accurately modelling the socio-economic impacts of Arctic ship accidents incurred by indigenous communities is necessary. Next steps include eliciting stakeholder feedback on the method and investigating how it may support existing efforts for safe Arctic shipping and risk assessment.

4.8. Acknowledgements

The financial support of the Lloyd's Register Foundation is acknowledged with gratitude. Lloyd's Register Foundation helps to protect life and property by supporting engineering-related education, public engagement and the application of research (grant number GA\100077).

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5. A METHOD FOR EVALUATING OPERATIONAL IMPLICATIONS OF REGULATORY CONSTRAINTS ON ARCTIC SHIPPING

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5.1. Co-authorship statement

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5.2. Abstract

Development of effective marine policy necessitates evidence-based, data-driven evaluations of the effects of regulatory constraints on operations. This is essential to better understand implications of policy decisions on complex socio-technical systems. This paper demonstrates a generalized methodology for evaluating operational implications associated with implementing maritime regulations. The method combines a ship performance model, regulatory constraint models, and multi-criteria pathfinding and optimization algorithms to evaluate and compare the operational implications of different

regulatory constraints. The method is applied to Arctic shipping. The Polar Operational Limit Assessment Risk Indexing System (POLARIS) and the Arctic Ice Regimes Shipping System (AIRSS) are considered. POLARIS and AIRSS are regulatory guidelines used to assign structural safety constraints on ships in ice. Four approaches for assigning structural safety constraints are modelled: 1) POLARIS, 2) AIRSS, 3) speed limits established through a first-principles ship-ice interaction model, and 4) navigation in the absence of structural safety constraints. Operational implications are measured as distance, voyage time, and fuel consumption. Route optimization is validated against expert opinion of Arctic ship captains. Results indicate AIRSS is the more conservative regulatory guideline, yet associated with decreased voyage time and fuel consumption. Implications for marine policy and safe navigation are that, while POLARIS offers flexibility to operate in more severe ice conditions, it increases voyage time, fuel consumption, and the risk of vessel damage. Competent Arctic seafarers are critical for safe and efficient operations. The generalized methodology provides marine policy-makers and industry stakeholders with a means to evaluate operational implications of maritime regulations.

5.3. Introduction

Regulations are intended to shape behaviours to address a problem. In addition to mitigating a problem of concern, there are costs associated with regulatory implementation. Regulations should be evaluated on their efficacy in addressing the problem and the associated costs [1,2].

Regulatory constraints can have significant implications on the operational objectives of a ship [5]. Implementation can be onerous on ship owners with respect to operational cost efficiency [6].

Effective marine policy requires evidence-based and data-driven evaluations of the implications of regulatory constraints on operations. Such evaluations allow policy-makers to consider the costs incurred by those responsible for implementing regulations, and support industry stakeholders in establishing economic implementation strategies.

A network of regulations govern the Arctic maritime industry, promoting, in part, safety of people, environment, and assets. Regulatory guidelines, such as the Canadian Arctic Ice Regime Shipping System (AIRSS) [3] and the International Maritime Organization (IMO) Polar Operational Limit Assessment Risk Indexing System (POLARIS) [4] promote safe navigation in ice by imposing structural safety constraints on Arctic ship operations.

Several studies have evaluated Arctic maritime regulations, including the Polar Code [7], POLARIS [8-13], and AIRSS [14]. These studies focus on regulatory efficacy, risk mitigation, and regulatory limitations. There is a gap in the research literature regarding methods to evaluate operational implications of Arctic maritime regulations.

The current study demonstrates a generalized methodology to evaluate the operational implications incurred under different maritime regulatory constraints. The method combines a ship performance model, regulatory constraint models, and multi-criteria pathfinding and optimization algorithms.

The ship performance model provides estimates of operational implications. Definition of multi-criteria cost function weights allows for prioritization of operational objectives.

The method is applied to the case of Arctic shipping. Four approaches for assigning structural safety constraints for ships in ice are modelled: the AIRSS and POLARIS regulatory guidelines, conservative speed limits established through a first-principles ship-ice interaction model [15], and navigation in the absence of structural safety constraints. Operational implications are measured as distance, voyage time, and fuel consumption.

To illustrate the method, optimal routes and speeds for a Polar Class 5 (PC5) vessel transiting the Northwest Passage are identified. Optimized routes and speeds are validated against the expert opinions of Arctic ship captains.

Expert opinion also provides insight into navigational hazards and ancillary issues which require consideration for safe navigation in ice. Scenarios in which regulatory constraints permit routing in unsafe conditions are discussed.

The method provides policy-makers with a means to evaluate the operational implications associated with maritime regulations. The method provides Arctic shipping stakeholders with a means to assess economic implementation strategies.

Evaluating the efficacy of AIRSS or POLARIS, or the likelihood of a ship to incur structural damage while operating under these regulatory guidelines, is outside the scope of the current study.

5.3.1. Safe navigation and operational constraints

Marine policy and regulation is central to the safe navigation of vessels in Arctic waters. The following section introduces regulatory instruments that promote safe Arctic navigation. Particular focus is given to the regulation of structural safety constraints for ships in ice.

The IMO has developed several treaties which promote safe navigation in all maritime regions. These include the International Convention for the Safety of Life at Sea (SOLAS) [16], the International Convention for the Prevention of Pollution from Ships (MARPOL) [17], and the International Convention on Standards of Training, Certification and Watchkeeping for Seafarers (STCW) [18].

Recognizing the increased risk of navigating in polar waters, the Polar Code was adopted as an amendment to SOLAS, MARPOL, and STCW. The Polar Code provides functional requirements for navigational safety, voyage planning, crew competency, and communication in polar regions.

The Polar Code requires that vessels establish operating limits and procedures through risk-based operational assessments. POLARIS is recommended through the Polar Code to assess operational capabilities and limitations of ships in ice.

Regulatory guidelines used to assign structural safety constraints on ships in ice have been in use for decades. Several Arctic nations have guidelines that pre-date POLARIS, including Canada, Russia, and Finland and Sweden [19,20].

Under Canadian jurisdiction, there are currently three guidelines in use to promote safe operations in ice. The Zone Date System (ZDS), AIRSS, and POLARIS [21]. These three guidelines are introduced in the following sections.

5.3.1.1. ZDS

In operation since 1972, the ZDS was the first methodology enforced under Canadian jurisdiction to promote safe operations in ice through operational constraints [22]. The ZDS segregates the Canadian Arctic into sixteen geographical regions, referred to as Shipping Safety Control Zones (SSCZs). SSCZs are established based on historical ice data. For a given vessel ice class, seasonal access periods are defined (i.e. entry and exit dates). A vessel can only operate in a SSCZ during the access period [21].

Access periods for SSCZs are fixed and do not account for year-over-year variability in ice conditions [23]. This is seen as a limitation as it provides mariners with no flexibility to navigate based on prevailing ice conditions [22].

5.3.1.2. AIRSS

Introduced in 1996, AIRSS offers flexibility over the ZDS through consideration of observed or forecasted ice conditions [22]. The methodology incorporates the concept of an ice regime, defined as an area with a relatively homogenous distribution of ice types, open water, and associated partial concentrations [3]. Ice types are defined by ranges of ice thickness.

The AIRSS methodology provides an evaluation of the risk of ice-induced structural damage to a vessel and restricts operations in higher risk ice regimes. Published Ice

Multiplier (IM) values provide a proxy of the nominal risk posed to a vessel by a given ice type in relation to its assigned ice class. Based on the vessel ice class and the ice regime, a resultant Ice Numeral (IN) value is calculated (Eq. 5.1).

$$IN = \sum_i IM_i \times C_i \tag{5.1}$$

where IM_i is the IM value of the ith ice type or open water, and C_i is the associated partial concentration in tenths.

AIRSS imposes a binary go/no-go operating criteria. A vessel can only enter an ice regime if the IN value is greater than or equal to zero [3].

5.3.1.3. POLARIS

The POLARIS methodology was introduced through the Polar Code in 2017. Recognizing speed as a risk factor for ice damage, POLARIS allows operation at reduced speed in ice regimes in which a vessel is considered to have marginal operational capability [19].

Influenced, in part, by AIRSS, POLARIS adopts the concept of an ice regime. A Risk Index Outcome (RIO) value is calculated for an ice regime using published Risk Index Values (RIVs) (Eq. 5.2). POLARIS RIO values and RIVs are analogous, but not equal, to AIRSS IN and IM values, respectively.

$$RIO = \sum_i RIV_i \times C_i \tag{5.2}$$

where RIV_i is the RIV of the ith ice type or open water, and C_i is the associated partial concentration in tenths [4].

Operating criteria are assigned based on the RIO value for a given vessel ice class. The following operating criteria are assigned for ice classes PC1 – PC7: 'Normal operation' for RIO ≥ 0, 'Elevated operational risk' for -10 ≤ RIO < 0, and 'Operation subject to special consideration' for RIO < -10. For ice classes below PC7, 'Operation subject to special consideration' is assigned for RIO < 0.

Reduced speed limits are suggested for 'Elevated operational risk'. Additional risk mitigating measured may be adopted, such as icebreaker escort and additional watching keeping. Under Canadian jurisdiction, a vessel may not enter an ice regime evaluated as 'Operation subject to special consideration' [22].

All three guidelines remain in use in the Canadian Arctic. AIRSS and POLARIS can be used to allow operation outside ZDS access periods. Polar Class (PC) vessels and any vessel constructed after 1 January 2017 can use POLARIS. Vessels constructed before 2017 can use either AIRSS or POLARIS [22].

Each guideline is intended to promote safe operations, yet, by design, they provide varying degrees of operational flexibility. It is assumed that the methodologies may provide different, and potentially contradictory, operational constraints. The objective of the current study is to evaluate and compare the operational implications of AIRSS and POLARIS. The ZDS is also discussed.

5.3.2. Speed limits in ice

Ships navigating in ice reduce speed to mitigate the risk of ice-induced structural damage to the vessel. A captain may reduce speed based on experience and due caution. Speed reductions may be imposed through regulatory guidelines, e.g. POLARIS. A detailed review of existing methodologies to estimate the maximum speed in ice at which damage can be avoided is provided by Dolny [15].

POLARIS recommends reduced speed limits in ice regimes in which a ship has marginal operating capability. The reduced speed limits were defined based on the International Association for the Classification of Ships, Unified Requirements for the design of PC vessels (IACS UR.I) [24] and experience and input from Arctic nations. IACS UR.I design points are based on an ice indentation pressure-area relationship integrated with an energy-limit collision model, developed by Daley [25].

In establishing POLARIS reduced speed limits, nominal limiting ice thicknesses were assigned to each PC, assuming operation in level ice (i.e. $10/10^{th}$ concentration). Limiting ice thickness values were established based on operational experience and data submitted from Canada, Russia, and Finland (i.e. Baltic). Recognizing speed as a risk factor for ice damage, a vessel is permitted to operate beyond the limiting level ice thickness if a reduced speed limit is used. To mitigate the risk of structural damage, reduced speed limits were established based on IACS UR.I design points [19,20].

Encountering uniform level ice is rare. In partial ice concentrations a ship experiences significantly less resistance and has greater capability than in level ice of the same thickness [19,26]. POLARIS evaluates operational capability through consideration of ice types and partial concentrations, allowing reduced speed limits to be linked to complex ice regimes. The technical background for the development of POLARIS is presented by IMO [19] and Bond et al. [20].

Speed limits in ice established through a first-principles ship-ice interaction model are presented by Dolny [15]. The approach integrates ship-ice interaction scenarios with models for collision mechanics, ice strength, and structural limit state. The collision mechanics and ice strength models are modified versions of those developed by Daley [25] and used in IACS UR.I [24].

The ship-ice interaction model considers speed, impact location, ice thickness, floe size, and ice strength. Two load limiting mechanisms are considered: momentum during ice crushing and flexural failure. Limit states are established through structural analysis. Structural capacity is defined as the plastic limit state. Speed limits are defined when ice loads exceed structural capacity.

Modelling structural capacity as the plastic limit state represents the point at which denting or permanent deformation would begin to occur. At these speed limits there would be no observable deformation of the hull and the loads would be below the actual structural capacity of the vessel. These speed limits are considered to be conservative [15].

Speed limits for PC vessels were established as a function of ice thickness and floe size. The current study models these speed limits as conservative structural safety constraints. The operational implications are compared against those of AIRSS and POLARIS.

5.3.3. Evaluating Arctic maritime regulations

The objective of a regulation is to change behaviours, individual or societal, in an effort to address a problem [1]. Regulations are evaluated on efficacy and the cost associated with implementation [2].

The IMO Formal Safety Assessment (FSA) guidelines [27] provide a structured risk-based procedure for policy-makers to evaluate maritime regulations. Three risk areas are considered: life-safety, environment, and property. There are five steps to the FSA procedure: hazard identification, risk analysis, identification of potential regulatory actions, cost-benefit analysis, and recommendations to decision-makers.

It is argued the regulatory cost assessment in the FSA is only partially addressed. The FSA does not consider the costs incurred by those responsible for regulatory implementation. Further, the FSA does not support maritime industry stakeholders in assessing how best to implement new regulations [6]. Policy-makers should consider the implications and costs imposed on all stakeholders, including ship owners, operators, coastal states, classification societies, and insurance underwriters [6,12].

An assessment of Arctic governance before and after adoption of the Polar Code is presented by Fedi [10]. The Polar Code has significant implications on Arctic coastal states, affecting their rights to regulate shipping in national waters. The onus is on coastal states to implement and enforce Polar Code provisions, and they must not introduce national regulations that contradict the Polar Code.

Several studies have evaluated POLARIS from the perspective of safe navigation and risk mitigation [8,9,11-13]. POLARIS is an effective risk-based decision-support tool for a number of stakeholders. Ship operators use POLARIS to support voyage planning and navigation. Ship owners use it to select an appropriate ice class during design. Coastal states, coast guard agencies, classification societies, and insurance underwriters use POLARIS to enforce and communicate expectations for safe navigation.

The efficacy of POLARIS in estimating and mitigating the risk of ice damage was validated by Kujala et al. [8]. Full-scale hull-ice load data and observed ice conditions were collected during voyages of two different vessels. First, the measured hull-ice loads were used to determine the necessary ice class to avoid ice damage. Second, POLARIS was used to determine the necessary ice class to allow transit through the observed ice conditions. POLARIS was shown to provide a reasonable approximation of the likelihood of ice damage.

Limitations of POLARIS have been highlighted [9,11]. POLARIS does not consider the human factor nor the risk associated with inexperienced Arctic crews. POLARIS is not mandatory under the Polar Code. POLARIS considers only the risk posed by ice conditions.

Despite the limitations, Fedi et al. [9] suggest that when combined, POLARIS and the Polar Code act as an effective risk mitigation tool for Arctic navigation.

Specific to Canadian Arctic regulations, a database of ship-ice damage events was used to assess the efficacy of AIRSS in predicting and mitigating ice damage [14]. In 17% of severe damage events (defined as a small hull puncture, large hole, or sinking), AIRSS produced a positive IN value, suggesting ice conditions were within operational limits of the vessel. In 19% of non-damage events, AIRSS produced a negative IN value, suggesting ice conditions were beyond operational limits.

Presently, there have been few evaluations of the operational implications of regulatory constraints on Arctic shipping. The current study uses a ship performance model to evaluate and compare the operational implications incurred under the POLARIS and AIRSS regulatory guidelines.

5.3.4. Modelling Arctic ship navigation

Arctic ship navigation models typically combine a ship performance model with pathfinding and route optimization algorithms. This section provides a discussion of existing methods for estimating ship performance in ice and a discussion of existing approaches for Arctic ship route selection.

5.3.4.1. Ship performance

Models for ship performance in ice include semi-empirical, probabilistic, and data-driven approaches. Detailed reviews of ship performance in ice modelling exist in the literature [28-32].

Semi-empirical ship performance models employ physics-based equations to estimate ship resistance in ice (e.g. Lindqvist [33], Riska et al. [34], and Keinonen et al. [26]). Data from ice tank tests have informed predictions of resistance in level ice [35] and pack ice [36].

An approach to estimate voyage time and fuel consumption along predetermined routes is presented by Frederking [37]. Ship performance follows Keinonen et al. [26], considering level ice resistance and available engine power. Ice data is obtained from published ice charts. Ice regimes are idealized as successive sections of level ice and open water. The current study employs the Frederking [37] approach to model ship performance in ice.

A similar approach for estimating voyage time and fuel consumption is used to evaluate the economic viability of Arctic routes [38]. Ship performance follows Riska et al. [34]. Discrete event simulation is used to evaluate ship performance along different routes. Probabilistic distributions of ice thickness and concentration are generated from satellite data.

Probabilistic approaches provide risk-based evaluations of ship performance. Full-scale voyage datasets have been combined with Bayesian networks (BNs) to estimate the probability of vessel besetting in ice.

Machine learning algorithms have been combined with BNs to link full-scale ship performance data with predicted ice conditions [31]. Another approach uses BNs to combine full-scale voyage data with expert knowledge on the risk factors and probabilities of occurrence for besetting [30].

Probabilistic approaches have been extended beyond single vessels to model the performance of multiple assets [39]. The approach combines probabilistic and discrete event simulations to evaluate the performance of a fleet of Arctic ships and port facilities.

Data-driven models rely on large datasets to identify correlations between system variables and make predictions [40]. Data-driven approaches use full-scale data sets, including voyage data and AIS traffic data, to predict vessel performance in ice [28,41].

A hybrid model is presented by Montewka et al. [42], integrating two methods to estimate ship speed. A simulation-based model estimates speed for a defined range of ice conditions. A data-driven model uses AIS data and sea ice data to estimate speed in ice. A heuristic, based on ice concentration, governs which speed estimate is used at a given time.

5.3.4.2. Route selection

Route selection in ice typically involves pathfinding and route optimization algorithms. In some instances, regulatory constraints are modelled. Reviews of route selection methods exist in the literature for Arctic [29,32] and non-Arctic [43] applications.

A route selection method for ships in ice, optimizing voyage time, is presented by Lehtola et al. [29]. The method incorporates forecasted sea ice data, bathymetric data, AIS data, and ship-ice and ship-ship interaction models. Navigation occurs over a discretized grid with ice data mapped to grid cells. Forecasted ice data and the associated speeds are updated in discrete time steps.

The ship-ice and ship-ship interaction models estimate attainable speed in ice. The ship-ship interaction model uses AIS data to estimate the influence that other ships have on speed and routing. Maximum attainable speed is a function of ice conditions, thus speed is constant in each grid cell. A modified A* pathfinding algorithm, considered equivalent to Dijkstra’s shortest-path algorithm, is used for route optimization.

Another approach to pathfinding in ice uses multi-criteria optimization and incorporates cost functions that reflect voyage time and navigational constraints for land and shallow water [32]. Resistance in ice is estimated using the Riska et al. [34] method. Ice conditions along the route are modeled probabilistically. Powell's cost-minimization algorithm is employed to identify the least-cost path.

Route selection in ice has been used to identify economic routes through Arctic waters [44].

Regions of interest are discretized with nodes and mapped with ice and environmental data. Speed is restricted using reduction factors based on the severity of ice and environmental conditions. At each node, operational and capital costs are calculated as functions of speed. Dijkstra's shortest-path algorithm is employed to identify the least-cost path.

The AIRSS and POLARIS regulatory guidelines have been modelled to support risk-based assessments of route feasibility. Routes are selected to mitigate the risk of structural damage to the vessel.

AIRSS is used to assess route feasibility through the Canadian Arctic [45]. The region of interest, discretized as a grid, is mapped with sea ice data from published ice charts. AIRSS IN values are calculated and cells with negative IN values are deleted from the model. Using only the remaining positive IN value regions, optimal routes are identified using Dijkstra's shortest-path algorithm. Linear distance is the only optimized parameter and ship performance is not considered.

A similar study, employing AIRSS and Dijkstra's shortest-path algorithm, is presented by Liu et al. [46]. Voronoi diagrams are used to produce routes that have a maximum safe distance between unnavigable ice regimes.

Dijkstra's shortest-path algorithm is prevalent in Arctic route selection applications [29,44-46]. Pareto optimization principles have been applied in non-Arctic applications [43,47].

A summary of existing methods for route selection in ice, including the current study, are presented in Table 5.1. There are several novelties of the current study.

Table 5.1. Comparison of existing methods for route selection for ships in ice and the method used for the current study.

Author. Year	**Ship performance**		**Navigational constraints**	**Decision factors**		**Pathfinding algorithm**	**Optimization criteria**		
	Speed	**Fuel cons.**		**Route**	**Speed**		**Voyage time**	**Distance**	**Fuel cons.**
Lehtola et al. 2019	✓	✕	Bathymetry, Narrow waterways, Ship-ship interaction.	✓	✓	Dijkstra's	✓	✕	✕
Kotovirta et al. 2009	✓	✕	Bathymetry.	✓	✕	Powell's	✓	✕	✕
Nam et al. 2013	✓	✕	Metocean conditions, Bathymetry.	✓	✕	Dijkstra's	✓	✕	✕
Etienne & Pelot. 2013	✕	✕	AIRSS, Proximity to shoreline.	✓	✕	Dijkstra's	✓	✓	✕
Liu et al. 2016	✕	✕	AIRSS.	✓	✕	Dijkstra's	✕	✓	✕
Current study	✓	✓	AIRSS, POLARIS, Speed limits based on structural analysis.	✓	✓	Multi-criteria Dijkstra's	✓	✓	✓

The ship performance model estimates both vessel speed and fuel consumption. Multiple structural safety constraints are modelled.

The existing methodologies assign a constant vessel speed based on ice conditions and other navigational constraints. The current study optimizes speeds within the limits imposed by structural safety constraints and available engine power.

The current study employs a multi-criteria form of Dijkstra's shortest-path algorithm. Routes and speeds in both ice and open water are optimized to minimize distance, voyage time, and fuel consumption.

5.4. Method

A method was developed to evaluate the operational implications of maritime regulations. The method incorporates three elements: a ship performance model, regulatory constraint models, and multi-criteria pathfinding and optimization algorithms.

The method is intended to support policy-makers evaluating the cost and operational implications of marine policy and industry stakeholders assessing economic implementation strategies. Steps required of an end-user applying the generalized methodology are outlined below:

1. Define vessel
2. Select environment & departure / arrival points
3. Model regulatory constraints
4. Define multi-criteria cost function weights
5. Execute route selection and optimization
6. Analyze optimized routes & operational implications

Definition of the multi-criteria cost function weights allows the end-user to prioritize operational objectives.

The method is applied here to Arctic shipping. A ship performance in ice model is adopted and Arctic maritime regulations that impose structural safety constraints for ships in ice are modelled.

The environment is modelled after a Canadian Ice Service (CIS) ice chart, as a discretized grid with a resolution of 8 km. An artificial agent, modelled as an ice class vessel, navigates the grid by selecting the direction of movement between grid cells and speeds within grid cells.

The agent adheres to imposed structural safety constraints, i.e. regulations. As the agent navigates the grid, operational implications are incurred. Operational implications are estimated using the ship performance model. Operational implications are measured as distance (km), voyage time (hours), and fuel consumption (tonnes). Optimal routes and speeds which minimize distance, voyage time, and fuel consumption are identified.

To illustrate the method, optimal routes for a PC5 vessel transiting the Northwest Passage from Lancaster Sound to Tuktoyaktuk are identified. Results are validated against the expert opinions of two Arctic ship captains with extensive knowledge of the region.

Elements of the method are illustrated in Figure 5.1 and detailed in Sections 5.4.1 to 5.4.3. The expert validation exercise is discussed in Section 5.4.4.

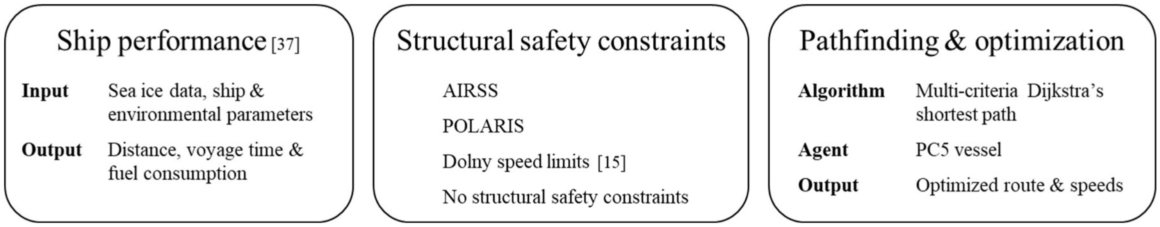

Figure 5.1. Elements of the method applied to Arctic shipping.

5.4.1. Ship performance model

A ship performance model is adopted to estimate the operational implications incurred under different regulatory constraints. The ship performance model and parameters are detailed in this section.

Predictions of distance, voyage time, and fuel consumption in ice and open water follow Frederking [37].

The ship hull structure under consideration is modelled after a PC5 vessel presented by Dolny [15]. Adopting this PC5 hull structure allows for the associated speed limit curves developed by Dolny [15] to be derived for the current study. Ship and environmental parameters used in the model are defined in Table 5.2.

Table 5.2. Ship and environmental parameters

Ship parameters			**Environmental parameters**		
Waterline length	L	75 m	Salinity factor	SAL	1
Beam	B	16 m	Ice surface temperature	T	-10 °C
Draft	D	6.5 m	Ice flexural strength	σ_f	750 kPa
Block Coefficient	C_b	0.625	Gravity	g	9.81 m/s^2
Average bow flare angle	γ	33.5°	Density of sea water	ρ_w	1.03 tonnes/m^3
Average buttock angle	β	32°			
Hull condition factor	HC	1			
Fuel consumption rate	FCR	0.17 tonnes/MW-hr			
Available engine power		8.5 MW			

Under IACS UR.I [24], a PC5 vessel is designed for year-round operation in medium first-year ice (70 – 120 cm thick), which may include old ice inclusions. The Polar Code [7] classifies PC5 as a Category A ship for the application of functional requirements in the code.

Level ice resistance predictions are based on empirical equations developed by Keinonen et al. [26]. Three components of resistance are calculated: open water resistance (Eq. 5.3), ice resistance normalized for a speed of 1 m/s (Eq. 5.4), and added ice resistance for speeds above 1 m/s (Eq. 5.5). Total resistance is the sum of the three components (Eq. 5.6).

Resistance is calculated in MN, V is ship speed in m/s, and h is ice thickness in m. All other variables are defined in Table 5.2.

For the current study, the required thrust to maintain speed is assumed to be equal to the total resistance. Required engine power is calculated using Eq. 5.7, based on empirical equations established by Keinonen et al. [26] and assuming 80% of engine power is absorbed at full speed. Fuel consumption is calculated as a function of engine power (Eq. 5.8)

Required engine power P is in MW, T is thrust in MN, *fuel consumption* is calculated in tonnes, and t is time in hours.

$$R_{OW} = (\rho_w LBDC_b)^{1.1}\left(0.025\left(V/\sqrt{gl}\right) + 8.8\left(V/\sqrt{gl}\right)^5\right)/1000 \tag{5.3}$$

$$\begin{aligned} R_{ice} = {} & 0.015(HC)(SAL)B^{0.7}L^{0.2}D^{0.1}h^{1.5}\left(1 - 0.0083(T + 30)\right) \\ & \times \left(0.63 + 0.00074\sigma_f\right)\left(1 + 0.0018(90 - \gamma)^{1.6}\right)\left(1 + 0.003(\beta - 5)^{1.5}\right) \end{aligned} \tag{5.4}$$

$$R_{ice}(V > 1\text{ m/s}) = 0.009(HC)((V-1)/(gL)^{0.5})B^{1.5}D^{0.5}h \times \left(1 - 0.0083(T+30)\right)(1 + 0.0018(90-\gamma)^{1.6})(1 + 0.003(\beta - 5)^{1.5}) \quad (5.5)$$

$$R_{Total} = R_{OW} + R_{ice} + R_{ice}(V > 1\text{m/s}) \quad (5.6)$$

$$P = T/0.8(0.122 - 0.0057V) \quad (5.7)$$

$$fuel\ consumption = FCR \times P \times t \quad (5.8)$$

Ice data is obtained from a CIS ice chart for the Western Arctic for 14 September 2020. Following World Meteorological Organization (WMO) nomenclature, ice regimes are reported using 'egg' codes. An 'egg' code reports the ice types (i.e. thickness ranges) and associated partial concentrations and floe sizes that comprise an ice regime. Terminology and procedures for reporting ice conditions using 'egg' codes are provided by CIS [48].

For the current study it was necessary to model ice thickness as discrete values. WMO ice type descriptions, codes, and thickness ranges, and the discrete ice thickness values modeled for the current study are presented in Appendix E (Table E.1). Floe size is not considered in the ship performance model.

The resistance equations assume uniform level ice [26]. Following Frederking [37], ice regimes are idealized as successive sections of level ice and open water. In a grid cell, the partial distance of each section of level ice is the product of the associated partial concentration for that ice type and the total distance travelled in the grid cell.

The attainable speed in ice is limited by the maximum available engine power. An available engine power of 8.5 MW is modelled based on that of icebreakers of similar vessel displacement, as presented by Keinonen et al. [26].

The attainable speed as a function of maximum available engine power is determined by manipulating Eq. 5.3 to Eq. 5.7. Following Frederking [37], in thicker ice, beyond the power capacity of the vessel for level ice breaking, a ramming operation is assumed [37]. Ramming is modeled with an average speed of 1 m/s at maximum available power (8.5 MW).

Within a grid cell, attainable speed will vary with ice thickness. For clarity, the average speed in a grid cell is reported.

An example average speed calculation is presented in Table 5.3. Transiting an 8 km grid cell with an ice regime comprised of 3/10th thin first-year and 2/10th thick first-year ice, is idealized as 2.4 km in 70 cm thick ice, 1.6 km in 2 m thick ice, and 4.0 km in open water. Thick first-year ice is modelled as a ramming operation at 1 m/s. Dividing total distance by total time in the grid cell, an average speed of 2.47 m/s is calculated.

Table 5.3. Example calculation of attainable average speed in a grid cell

Ice type & open water	**Thickness (m)**	**Partial conc. (tenths)**	**Partial dist. (m)**	**Max speed (m/s)**	**Time (hr)**
Thin first-year	0.7	3	2.4	2.75	0.24
Thick first-year	2.0	2	1.6	1.00	0.44
Open water	-	5	4.0	8.87	0.13
			Total time (hr)		**0.81**
			Average speed (m/s)		**2.74**

In this example the attainable average speed is calculated. The agent may adopt a reduced speed to optimize voyage time and fuel consumption or based on speed limits imposed through structural safety constraints, described in Section 5.4.2.

5.4.2. Structural safety constraints

Four different approaches for assigning structural safety constraints are modelled. The POLARIS and AIRSS regulatory guidelines, speed limits established through a first-principles ship-ice interaction model [15] (hereafter referred to as Dolny speed limits), and navigation in the absence of structural safety constraints. The four approaches are modelled and evaluated separately.

Under AIRSS, operational constraints are assigned based on calculated IN values for a PC5 vessel. Following Transport Canada guidance, a PC5 vessel is treated as equivalent to a Canadian Arctic Class (CAC) 4 [49].

In each ice covered grid cell, ice regime 'egg' code data are used to assign IM values and partial concentrations. The IN value is calculated as per Eq. 5.1.

If $IN \geq 0$, speed in the grid cell is unconstrained. If $IN < 0$, entry into the grid cell is prohibited.

POLARIS is modelled similar to AIRSS. Operational constraints are assigned based on calculated RIO values for a PC5 vessel. In each ice covered grid cell, ice regime 'egg' code data are used to assign RIVs and partial concentrations. The RIO value is calculated as per Eq. 5.2.

If $RIO \geq 0$, speed in the grid cell is unconstrained. If $-10 \leq RIO < 0$, the maximum allowable speed in the grid cell is reduced to the POLARIS recommended speed limit for a PC5: 2.5 m/s [4]. If $RIO < -10$, entry into the grid cell is prohibited.

The ice type definitions used to assign AIRSS IM values and POLARIS RIVs do not align with WMO nomenclature reported in CIS ice charts. For the current study, it was necessary to link RIVs and IM values to WMO ice types. WMO ice type descriptions and codes, and associated IM values and RIVs are presented in Appendix E (Table E.2).

AIRSS and POLARIS support the use of icebreaker escort to allow operation in more severe ice regimes. Note that the current study does not model the implications of icebreaker escort. AIRSS and POLARIS also support a modified risk evaluation accounting for summer ice decay. Note that the current study does not consider decayed ice.

The third approach is Dolny speed limits established for a PC5 vessel. Dolny speed limits provide a conservative benchmark to compare against POLARIS and AIRSS.

Speed limits are a function of ice thickness and floe size. Ice thicknesses ranged from 0 to 3 m and four discrete floe size widths were modelled: 25, 50, 100, and 200 m.

WMO floe size nomenclature cover higher width ranges than modelled by Dolny. For the current study it was necessary to test the behaviour of Dolny speed limits with increasing floe size. Manipulating data presented by Dolny [15], speed limits are plotted as a function of floe size for five ice thickness values (Figure 5.2).

Floe size does not influence speed limits at ice thickness of 70 cm and below. For ice thickness above 70 cm, speed limits converge asymptotically with floe size, reaching a limit of 1.34 m/s at 200 m.

The convergent behaviour justifies the application of speed limits established for 200 m wide floes to the larger WMO floe sizes reported in the ice chart data. WMO floe size descriptions, codes, and width ranges, and the floe size widths modelled for the current study are presented in Appendix E (Table E.3).

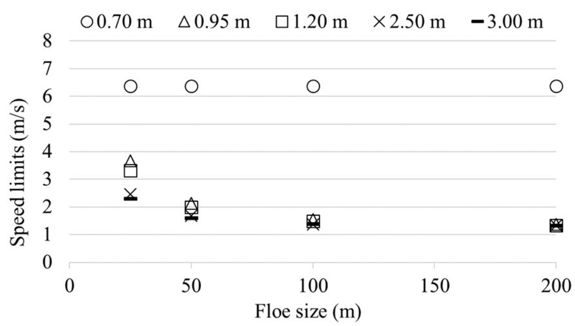

Figure 5.2. Speed limits with increasing floe size for a range of ice thickness value (modified from Dolny [15])

Whereas POLARIS assigns a single limit speed for an ice regime (or grid cell), Dolny speed limits are defined for each ice type and floe size combination reported in an ice regime. Dolny speed limits used for the current study, modelled as a function of ice thickness and floe size, are presented in Table 5.4.

Table 5.4. Dolny speed limits (m/s) as a function of ice thickness and floe size for a PC5 vessel.

Ice thickness (m)	Floe size (m)			
	25	50	100	200
0.10	N/A	N/A	N/A	N/A
0.15	N/A	N/A	N/A	N/A
0.30	N/A	N/A	N/A	N/A
0.50	N/A	N/A	N/A	N/A
0.70	6.37	6.37	6.37	6.37
0.95	3.67	2.13	1.55	1.38
1.20	3.31	2.00	1.48	1.34
2.00	2.72	1.74	1.43	1.34
2.50	2.46	1.68	1.38	1.34
3.00	2.31	1.60	1.39	1.34

5.4.3. Pathfinding and optimization

The current study uses a multi-criteria form of Dijkstra's shortest-path algorithm for pathfinding [50]. Routes and speeds are optimized to minimize distance, voyage time, and fuel consumption, while adhering to imposed structural safety constraints. The general framework for pathfinding and optimization is presented in Figure 5.3.

An artificial agent navigates an environment modelled after a CIS ice chart, discretized as a grid with a resolution of 8 km. Grid cells are mapped as ice covered, open water, or land. Sea ice data is obtained from the ice chart.

The centres of grid cells are represented by vertices. At any time, the agent occupies the centre vertex of a grid cell. At each grid step, there are eight directions of travel available to transit to neighbouring grid cells: four cardinal directions (e.g. north) and four inter-cardinal directions (e.g. northeast).

Distance, voyage time, and fuel consumption are accrued with each grid step. A scalarized multi-criteria cost function is used to aggregate the values for distance, voyage time, and fuel consumption into a single aggregated cost, W, for each grid step (Eq. 5.9).

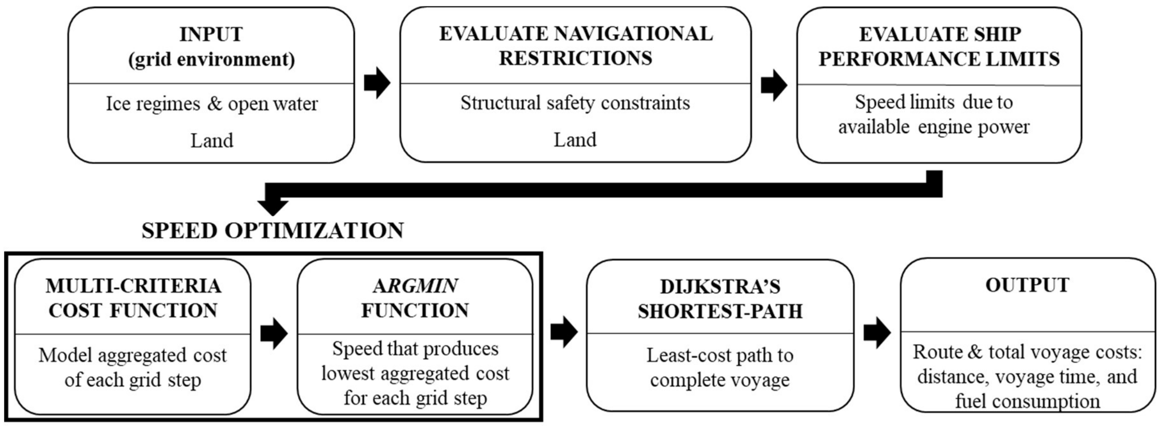

Figure 5.3. General framework for pathfinding and optimization.

$$W(U,U',V) = k \times distance(U,U') + m \times voyage\ time(U,U',V) + l \times fuel\ consumption\ (U,U',V), \tag{5.9}$$

where the agent is travelling from grid cell vertices *U* to *U'*, and *k*, *m*, and *l* are weights for the cost function elements of distance, voyage time, and fuel consumption, respectively.

The modelled cost function weights [k, m, l] influence the optimized route and speeds. Three scenarios for cost function weight ratio are evaluated in the current study: [1, 1, 1], [1, 1, 10], and [1, 10, 100].

Distance is a function of grid cell geometry and direction of travel. Travelling in a cardinal direction corresponds to a distance equal to the grid cell resolution (i.e. 8 km). Travelling in an inter-cardinal direction corresponds to the diagonal distance across a grid cell (i.e.

8 x √(2) km). Voyage time and fuel consumption are estimated using the ship performance model and are functions of speed and the ice regime of the grid cell into which the agent is entering.

Note that the aggregated cost, *W*, of a grid step is sensitive to the units used for measuring the cost function elements (e.g. km, hours, tonnes). Techniques and procedures to establish multi-criteria weighting schemes and integrate elements with different units of measure is outside the scope of the current study.

Navigational restrictions and ship performance limitations must be considered. The agent cannot occupy grid cells mapped as land and must adhere to imposed structural safety constraints. Structural safety constraints may prohibit entry or impose speed limits in certain grid cells (Section 5.4.2). The maximum attainable speed of the vessel in ice and open water will be limited by the available engine power of the vessel, as determined by the ship performance model (Section 5.4.1).

When entry into a grid cell is prohibited, the total cost of that grid step is set to $+\infty$, effectively discouraging this route option. When speed limits are imposed, the available range of speeds is capped at the speed limit.

The optimized speed for each grid step is predetermined based on the ice conditions (and open water) and the aggregated cost, *W*. A speed optimization algorithm uses the mathematical *argmin* function to identify the speed that produces the lowest aggregated cost, *W*, for each grid step (Eq. 5.10). Available speeds range from 0.5 to 10 m/s in half integer increments.

$$V^* = \underset{V}{\operatorname{argmin}} W(U, U', V) \tag{5.10}$$

where $V*$ is the optimized speed.

With the optimized speed and aggregated cost of each grid step established, Dijkstra's shortest-path algorithm is used to search the grid environment and identify the least-cost path between designated departure and arrival points.

The model outputs the optimized route and the total accumulated distance, voyage time, and fuel consumption for the voyage.

Calculation of the aggregated cost for each grid step in a simplified 3 × 3 grid is demonstrated in Appendix F.

A conceptual model of the route selection method is presented by Tran et al. [51]. The conceptual model uses reinforcement learning algorithms for pathfinding and optimization. Dijkstra's shortest-path algorithm is used for the current study as it is suitable for deterministic environments and offers greater computational efficiency over reinforcement learning.

5.4.4. Elicitation of expert knowledge

Model results were validated against the expert opinions of two ship captains, each with over twenty-five years of experience navigating in Arctic and sub-Arctic Canadian waters. The captains were provided with the same ice chart used in the model. Ship particulars were provided. An engine power rating was not provided.

The captains were tasked with plotting a route for a PC5 vessel transporting cargo from Lancaster Sound to Tuktoyaktuk. In addition to waypoints, the captains were asked to specify speeds along the route.

The captains worked separately and were not directed to use any specific regulatory guidelines, e.g. POLARIS, AIRSS, or ZDS. The captains provided explanations of their decision-making, including alternate viable routes, hazardous regions, and regions considered unnavigable.

5.5. Results

Model results are presented for the four approaches for assigning structural safety constraints: AIRSS, POLARIS, Dolny speed limits, and navigation in the absence of structural safety constraints. To demonstrate the influence of cost function weights, three sets of model results are presented (Section 5.5.1.1 to Section 5.5.1.3). Results of the expert validation exercise are presented in Section 5.5.2.

5.5.1. Model results

5.5.1.1. Equal priority cost function: [1, 1, 1]

The first set of results used an equal weighting for [distance, voyage time, fuel consumption] of [1, 1, 1]. The optimal route under AIRSS is presented in Figure 5.4. The operational implications are presented in Table 5.5, with each ice regime and section of open water presented separately.

Table 5.5. Operational implications; AIRSS; cost function weights: [1, 1, 1].

Ice regime	Average speed (m/s)	Distance (km)	Voyage time (hr)	Fuel consumption (tonnes)
OW_1	6.5	48.1	2.1	0.8
SS	3.1	183.8	16.5	17.4
OW_2	6.5	2218.5	94.8	36.1
	TOTAL	2450.5	113.3	54.3

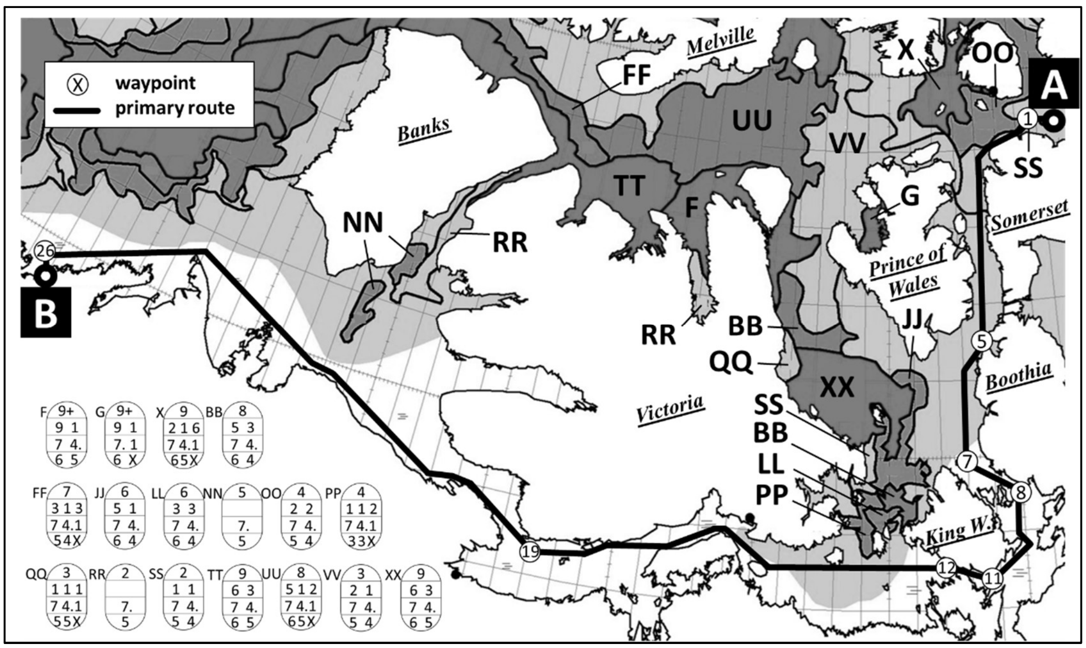

Figure 5.4. Optimal route; AIRSS; cost function weights: [1, 1, 1].

The route is primarily in open water, with an optimized open water speed of 6.5 m/s. The agent navigates south through Peel Sound (waypoints 1 to 5) and selects an open water route to the east of King William Island. Once around King William Island, the agent proceeds through open water for the remainder of the voyage to Tuktoyaktuk, waypoints 12 to 26.

Ice regime SS produces a positive IN value, allowing navigation through the ice regime. The optimized speed is reduced to 3.1 m/s and fuel consumption is increased, reflecting the presence of thick first-year (1/10th) and old ice (1/10th).

This is the only permissible route under AIRSS. In Victoria Strait (Victoria Island to the west, King William Island to the east), ice regimes XX, JJ, BB, and LL, produce negative IN values. There is no viable route through the strait.

The optimal route under POLARIS is presented in Figure 5.5. Operational implications along the route are presented in Table 5.6.

Table 5.6. Operational implications; POLARIS; cost function weights: [1, 1, 1].

Ice regime	**Average speed (m/s)**	**Distance (km)**	**Voyage time (hr)**	**Fuel consumption (tonnes)**
OW_1	6.5	99.1	4.5	1.6
OO	2.0	75.0	9.6	10.9
X	2.5	71.8	0.3	10.3
OW_2	6.5	95.8	4.3	1.5
VV	2.5	19.3	2.3	2.5
UU_1	1.5	118.3	23.1	29.7
OW_3	6.5	272.5	12.4	4.4
UU_2	1.5	8.0	1.6	2.0
FF	2.0	33.9	4.9	5.9
TT	1.1	88.3	24.5	32.1
RR	3.1	107.6	10.3	10.1
OW_4	6.5	79.0	3.6	1.3
NN	1.7	56.4	9.6	11.8
OW_5	6.5	547.1	24.8	8.8
	TOTAL	1672.0	135.9	132.8

The agent selects the shortest possible route through the Northwest Passage: west through Viscount-Melville Sound (waypoints 1 to 9) and southwest through Prince of Wales Strait (waypoints 12 to 14).

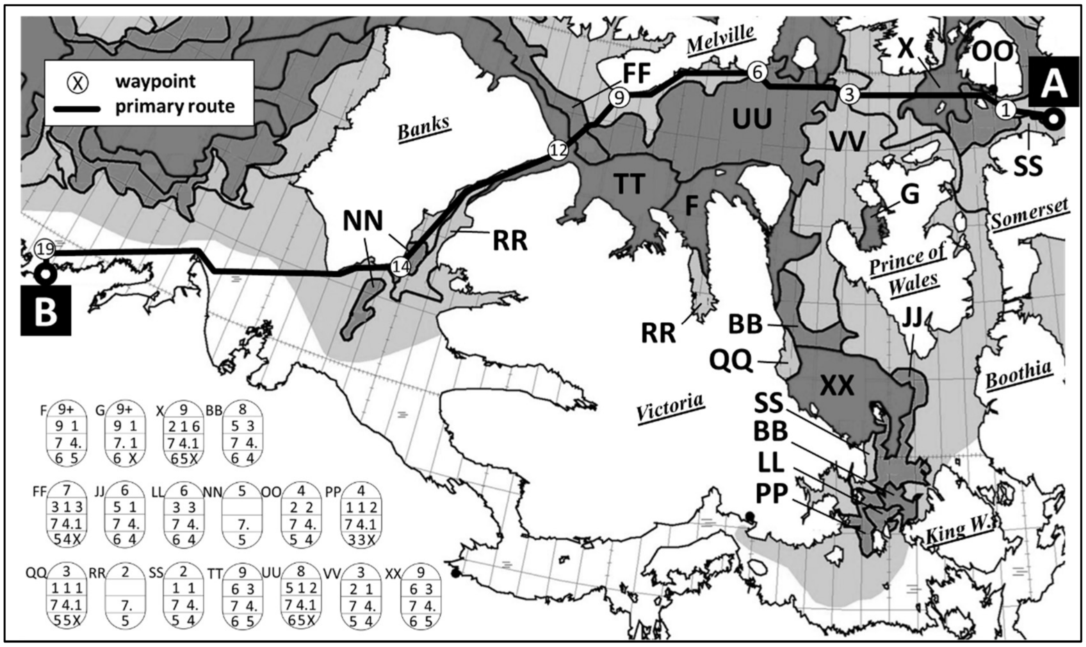

Figure 5.5. Optimal route; POLARIS; cost function weights: [1, 1, 1].

All encountered ice regimes produce positive RIO values with the exception of ice regime TT. Speed in positive RIO ice regimes is unconstrained and optimized based on the cost function and available engine power.

The optimized speed in ice is increased or decreased corresponding to increases or decreases in severity of ice conditions. The agent can be seen to maximize time in open water. For example, the agent proceeds northwest through ice regime UU toward the coast of Melville Island (waypoint 6) and follows open water towards Prince of Wales Strait (waypoint 12).

Ice regime TT is the most severe ice encountered along the route, containing 6/10th of old ice and 3/10th of thick first-year, and producing an RIO value of -9. The maximum allowable speed in TT is limited by the POLARIS speed limit of 2.5 m/s. Despite the

POLARIS speed limit, speed in the partial concentrations of thick first-year and old ice is actually curtailed by available engine power, to 1 m/s. The average speed in TT is 1.1 m/s.

Operating under both Dolny speed limits and no structural safety constraints, the optimal route is identical to POLARIS. Optimized speeds are the same with the exception of ice regime TT. There is no POLARIS speed limit and the agent adopts the optimized open water speed in the 1/10th partial concentration of open water. Speed in the thick first-year and old ice is curtailed by available engine power.

Navigating under Dolny speed limits, optimized speeds are identical to those under no structural safety constraints. The limiting factor is available engine power. In thicker ice, the vessel is not capable of attaining speeds sufficient to reach plastic limit states of the hull.

5.5.1.2. Prioritizing fuel consumption: [1, 1, 10]

To demonstrate the impact that cost function weights have on route optimization, results for a weight ratio for [distance, voyage time, fuel consumption] of [1, 1, 10] are presented. Fuel consumption is prioritized by a factor of ten.

There is only one permissible route under AIRSS, thus it is identical to that selected with an equal priority cost function (Figure 4). The agent travels through Peel Sound and selects the open water route to the east of King William Island. Operational implications are presented in Table 5.7.

Table 5.7. Operational implication; AIRSS; cost function weights: [1, 1, 10].

Ice regime	Average speed (m/s)	Distance (km)	Voyage time (hr)	Fuel consumption (tonnes)
OW_1	4.0	48.1	3.3	0.4
SS	2.5	183.8	20.4	16.4
OW_2	4.0	2218.5	154.1	16.3
	TOTAL	2450.5	177.8	33.1

Despite identical routing, the change in cost function weights results in adjusted speeds and changes in operational implications of voyage time and fuel consumption. In general, when fuel consumption is prioritized, the agent adopts reduced speeds compared to the equal priority weighting. The optimized open water speed is 4.0 m/s. Speed in ice regime SS is reduced to 2.5 m/s.

The optimal route under POLARIS is presented in Figure 5.6 and operational implications in Table 5.8. It is distinctly different than the POLARIS route under the equal weighting [1, 1, 1].

Table 5.8. Operational implications; POLARIS; cost function weights: [1, 1, 10].

Ice regime	Average speed (m/s)	Distance (km)	Voyage time (hr)	Fuel consumption (tonnes)
OW_1	4.0	48.2	3.4	0.4
SS	2.5	183.8	20.5	16.6
OW_2	4.0	497.5	34.6	3.7
BB	1.1	16.1	3.9	5.4
OW_3	4.0	1511.2	105.2	11.2
	TOTAL	2256.8	167.5	37.3

The agent proceeds south through Peel Sound and selects a route through Victoria Strait. The agent maximizes time in open water by following the west coast of King William Island. The agent passes briefly through ice regime BB (waypoints 10 to 12), which produces an RIO value of -4. The maximum allowable speed in BB is limited by the POLARIS speed limit of 2.5 m/s.

As before, speed in the partial concentrations of thick first-year and old ice is curtailed by available engine power, to 1 m/s. Beyond the ice in Victoria Strait, the agent proceeds through open water for the remainder of the voyage to Tuktoyaktuk (waypoints 12 to 31).

Note that BB is the only ice regime in Victoria Strait that produces a negative RIO value. The agent could have strategically navigated through JJ, SS, LL, and PP, to avoid the POLARIS speed limit required in BB. Instead, the optimal route minimizes time spent in ice by following the open water along the coast of King William Island.

Similar to the previous set of results, when operating under both Dolny speed limits and no structural safety constraints, the optimal route is identical to POLARIS. In ice regime BB there is no POLARIS speed limit and the agent adopts the optimized open water speed in the $2/10^{th}$ partial concentration of open water. In the thick first-year and old ice, speed remains curtailed by available engine power.

As seen in the previous results, optimized speeds under Dolny speed limits are identical to those under no structural safety constraints. The limiting factor is available engine power and the vessel is not capable of attaining speeds sufficient to reach plastic limit states of the hull.

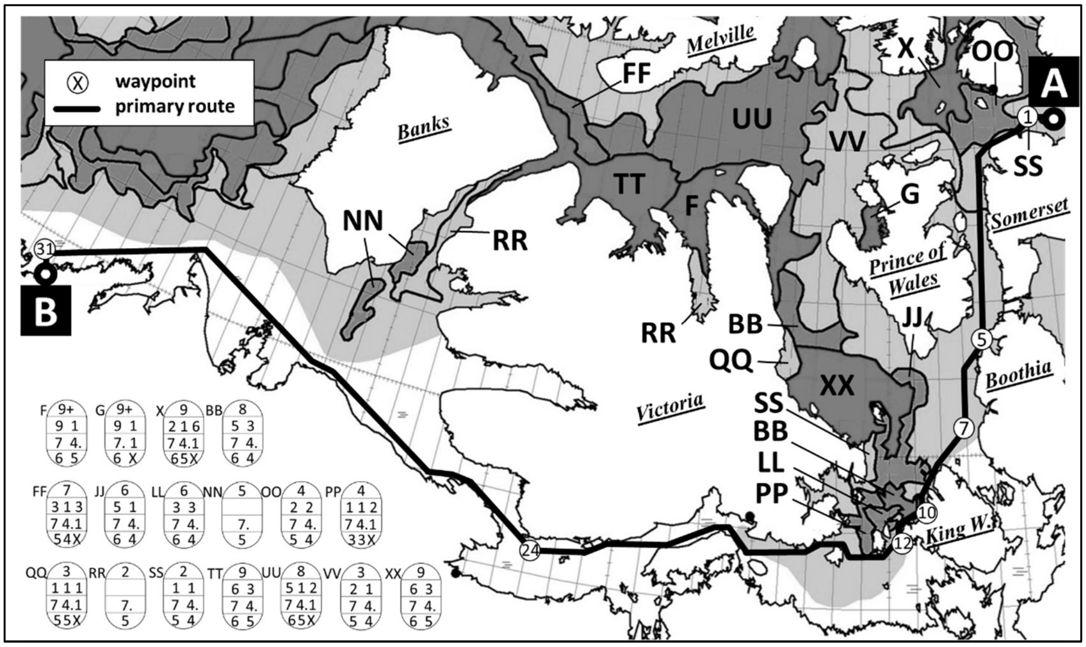

Figure 5.6. Optimal route; POLARIS; cost function weights: [1, 1, 10].

5.5.1.3. Prioritizing voyage time and fuel consumption: [1, 10, 100]

The final set of model results have voyage time prioritized by a factor of ten and fuel consumption prioritized by a factor of one hundred. The weight ratio for [distance, voyage time, fuel consumption] is [1, 10, 100].

The optimal routes under each approach are the same, and aside from some slight deviations are equivalent to the previous routes selected under AIRSS (Figure 5.4). The agent selects a route south through Peel Sound and to the east of King William Island. Optimized speeds are the same as under the weight ratio [1, 1, 10], at 4 m/s in open water and 2.5 m/s in ice regime SS.

Total distance, voyage time, and fuel consumption incurred under the four approaches for assigning structural safety constraints are summarized. Results are separated by cost function weight ratio for [distance, voyage time, fuel consumption], with [1, 1, 1] presented in Table 5.9, [1, 1, 10] in Table 5.10, and [1, 10, 100] in Table 5.11.

With a weight ratio of [1, 1, 1] and operating under POLARIS, Dolny speed limits, and no structural safety constraints ("None"), the agent selects the shortest route through the Northwest Passage. The route is shorter than AIRSS, yet voyage time and fuel consumption are significantly higher. Transiting the ice conditions in Viscount Melville Sound and Prince of Wales Strait requires reduced speeds and higher engine powers, which increases fuel consumption.

With a weight ratio of [1, 1, 10] and operating under POLARIS, Dolny speed limits, and no structural safety constraints, the agent selects a route through Victoria Strait. Compared to the results with the weight ratio [1, 1, 1], this is a longer route but it decreases the time spent in ice. Distance and voyage time increase, but fuel consumption is reduced by 72%.

Operating under AIRSS ([1, 1, 10]), there is no change in the route. However, with fuel consumption prioritized, the agent adopts reduced speeds. Fuel consumption is reduced by 39% compared to the results with the weight ratio of [1, 1, 1].

Table 5.9. Operational implications; cost function weight ratio: [1, 1, 1].

	AIRSS	**POLARIS**	**Dolny**	**None**
Distance (km)	2450	1672	1672	1672
Voyage time (hr)	113	136	135	135
Fuel consumption (tonnes)	54	133	133	133

Table 5.10. Operational implications; cost function weight ratio: [1, 1, 10].

	AIRSS	**POLARIS**	**Dolny**	**None**
Distance (km)	2450	2257	2257	2257
Voyage time (hr)	178	168	168	168
Fuel consumption (tonnes)	33	37	37	37

Table 5.11. Operational implications; cost function weight ratio: [1, 10, 100].

	AIRSS	POLARIS	Dolny	None
Distance (km)	2465	2465	2465	2465
Voyage time (hr)	178	178	178	178
Fuel consumption (tonnes)	32	32	32	32

With the weight ratio of [1, 1, 10], the AIRSS route (east of King William Island) is longer but fuel consumption is reduced compared to the other constraint approaches. The ice encountered in Victoria Strait requires reduced speeds and increases fuel consumption.

With a weight ratio of [1, 10, 100], total distance, voyage time, and fuel consumption are the same for each approach for assigning structural safety constraints. The agent selects identical routes and speeds under each approach (east of King William Island). There are slight deviations in the routing which result in the lowest fuel consumption of all results. This reflects the increased weight of 100 applied to fuel consumption.

5.5.2. Expert validation

Two Arctic ship captains were provided with the same CIS regional ice chart implemented in the model. The captains identified optimal routes for a PC5 vessel transiting from Lancaster Sound to Tuktoyaktuk.

Expert opinion provides validation of the routes identified through pathfinding and optimization. Further, it provides insight into navigational hazards which require consideration for safe navigation in ice that may not be reflected in the modelled regulations and route optimization.

Routes, speeds, and factors considered in the captains' decision-making are presented in Section 5.5.2.1. Navigational hazards and ancillary issues raised by the captains are discussed in Section 5.5.2.2.

5.5.2.1. Selected routes

Primary and alternate routes are presented in Figure 5.7. The primary route is identified with a solid line, alternate routes are identified with dotted lines.

Note that the captains referred to the ZDS and AIRSS in evaluating viable routes. Both captains were aware of POLARIS but have not used it in practice in the Canadian Arctic.

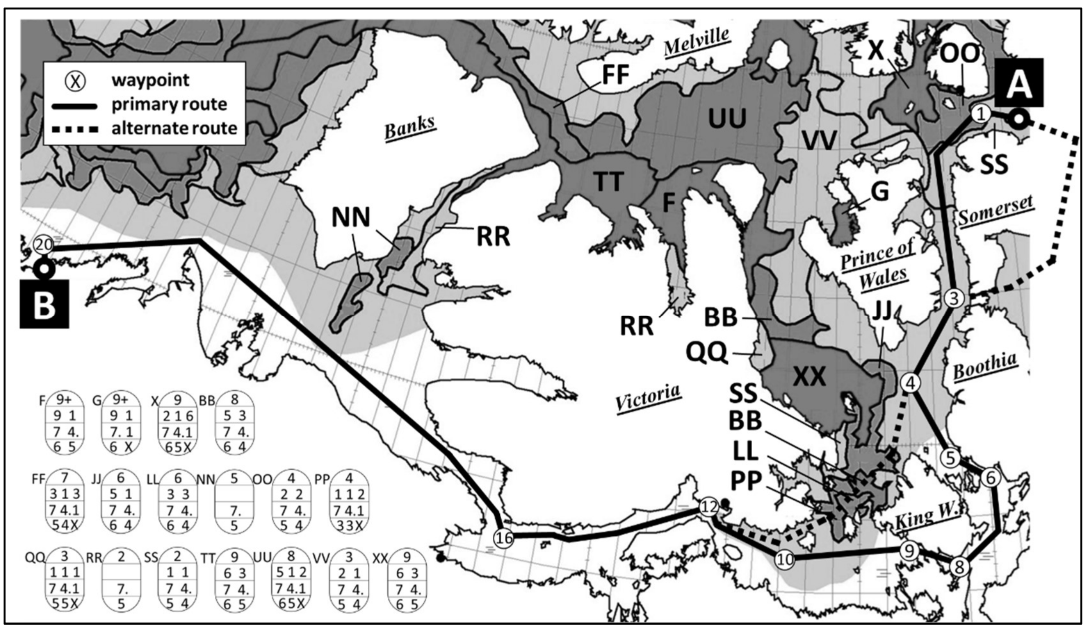

Figure 5.7. Primary and alternate routes identified through expert opinion

The primary route is through Peel Sound, waypoints 1 to 4. Ice regimes SS and OO produce positive IN values, allowing navigation in the region. Despite positive IN values, a reduced speed of 2.6 to 3.6 m/s (5 to 7 knots) is adopted due to the presence of old ice. Should visibility deteriorate in the presence of old ice, a further reduction in speed would be required. Beyond the ice in Peel Sound, the ship returns to full speed.

The primary route continues to the east of King William Island, through James Ross Strait, (waypoints 5 and 6) and Simpson Strait, (waypoints 8 to 9). Full speed in open water can be maintained. West of Simpson Strait, full speed is maintained for the remainder of the voyage to Tuktoyaktuk (waypoints 9 to 20). Caution would be exercised near the band of ice south of Banks Island (ice regime NN).

Comparing model results against the results of the expert validation exercise, the captains use “full speed” in open water and reduce speed to 2.6 to 3.6 m/s in the presence of old ice (ice regimes SS and OO). These speeds align well with model results under the equal priority cost function [1, 1, 1]. The agent selects 6.5 m/s (13 knots) in open water, considered to be a reasonable economic open water speed. In ice regime SS, the agent reduces speed to 3.1 m/s. Note that design speed was not defined for the expert validation exercise.

Two deviations from the primary route were suggested. Expressing concern with the high concentrations of old ice north of Peel Sound (ice regimes OO and X), one of the captains proposed an alternate route east through Lancaster Sound and south through Prince Regent Inlet (east of Somerset Island). The alternate route extends outside the boundary of the ice chart. The alternate route returns to Peel Sound through Bellot Strait (waypoint 3).

Experience suggests the route is typically ice free, and assuming good visibility, full speed in open water can be maintained. One captain stated that open water is almost always preferable to ice because it is safer and faster.

Victoria Strait is identified as an alternate route. Under AIRSS, transiting Victoria Strait would require icebreaker escort due to the high concentrations of old ice, which produce negative IN values (ice regimes XX, JJ, BB, and LL). One of the captains suggested that if an icebreaker is available, Victoria Strait is the preferred option as it is significantly shorter than the open water route east of King William Island. Vessel speed under icebreaker escort would be as slow as possible, in the range of 1.5 to 2.1 m/s (3 to 4 knots), depending on the width of the channel created by the icebreaker.

5.5.2.2. Navigational hazards and ancillary issues

The captains reported navigational hazards along both the primary and alternate routes that were factored into their decision-making.

Sea ice drifts under environmental forcing and results in a degree of uncertainty in the ice conditions reported in an ice chart. This is of particular concern when severe ice regimes are in proximity of a route.

There are high concentrations of old ice north of Peel Sound. Based on experience, the captains know the nominal ice drift direction in the region is south. This poses a risk of the vessel becoming beset in ice in Peel Sound. This was a justification for the alternate route east of Somerset Island.

The alternate route east of Somerset Island requires passage through Bellot Strait. Bellot Strait is a narrow channel with extreme currents. If there were any ice in the strait it would pose a significant risk of vessel damage and the region should be avoided.

In general, hydrographic surveying in the Arctic is limited and concentrated on traditional routes, such as Peel Sound and Victoria Strait. There are hydrographic issues and draft limitations that were considered when selecting viable routes.

The route east of King William Island has only recently been hydrographically surveyed and not in its entirety. Surveying in James Ross Strait is limited and Simpson Strait is particularly difficult to navigate. Vessel draft must be considered when evaluating these regions. The vessel under consideration has a draft of 6.5 m, allowing transit. The captains note that prior to being surveyed, the route east of King William Island would not be a viable option.

There are also draft limitations in Victoria Strait. Vessels cannot strategically navigate to avoid severe ice conditions. Routes must adhere to nautical charts and stay within surveyed regions.

A route through M'Clintock Channel (Victoria Island to the west, Prince of Wales Island to the east) is not a viable option. Hydrographic surveying in M'Clintock Channel is insufficient to support safe navigation.

A route west through Viscount-Melville Sound and Prince of Wales Strait is the shortest possible route, but is prohibited under the ZDS and AIRSS. The region is encompassed by SSCZ 2 and a PC5 vessel (recommended to be treated as a Type A in the ZDS [49]) is prohibited to enter at any time of year. Under AIRSS, ice regimes FF and TT produce negative IN values, preventing entry to Prince of Wales Strait.

POLARIS does allow transit through Viscount-Melville Sound and Prince of Wales Strait. This is observed in the model results. In follow up discussions, the captains expressed concern with POLARIS allowing a PC5 vessel to enter an ice regime with 6/10th old ice and 3/10th thick first-year. One captain stated they would be hesitant to bring a heavy Arctic icebreaker into such severe ice conditions.

The captains highlighted issues and tradeoffs with the ZDS and AIRSS. The ZDS does not consider actual observed ice conditions. Vessels can be prohibited from entering a SSCZ when actual ice conditions are favourable. Alternatively, and more concerning with respect to ship-ice damage, vessels can be permitted entry into SSCZs when actual ice conditions are beyond the operating limits of the vessel. While AIRSS provides ship operators with flexibility, the captains have experienced scenarios in which ice regimes that are assessed as safe (IN ≥ 0), were, in their opinion, beyond the operational limits of the vessel.

The ZDS, AIRSS, and POLARIS can allow a vessel to enter ice conditions in which it has only marginal or no operating capability. The captains emphasized that using regulatory guidelines to push the operating limits of a vessel is a risk prone practice.

5.6. Discussion

5.6.1. Main findings

A generalized methodology to evaluate the operational implications of maritime regulations was presented. The method was applied to the case of Arctic shipping. Main findings specific to the considered Arctic shipping scenario are discussed.

AIRSS provides a more conservative assessment of vessel capability in ice relative to POLARIS and the other approaches. The binary go/no-go operating criteria offers less flexibility in navigational decision-making. For the example considered here, there is only one permissible route under AIRSS, requiring increased distance to avoid severe ice regimes.

The optimal route under AIRSS is primarily in open water, allowing for increased speed at lower engine power. Despite the increased distance, voyage time and fuel consumption are decreased in comparison to POLARIS and the other approaches.

POLARIS is the less conservative regulatory guideline, offering flexibility to operate at reduced speeds in marginally capable ice regimes. While POLARIS provides the opportunity to select shorter routes, operating in severe ice regimes requires reduced speeds and higher engine power, which meant voyage time and fuel consumption are increased.

This supports the opinion of the captains that a route through open water is often safer and faster than a route through ice.

Navigating under both the Dolny speed limits and no structural safety constraints produce equivalent results, and are similar to POLARIS. The ship-ice interaction analysis used to establish the Dolny speed limits is considered conservative [15]. However, available engine power is the limiting factor in operating speed in more severe ice regimes. The vessel is not capable of attaining speeds sufficient to reach the plastic limit states of the hull structure.

Installed engine power was consistent with icebreakers of similar displacement [26]. Modelling a vessel with a higher available power would better illustrate the difference in operational implications between the Dolny speed limits and the approaches for assigning structural safety constraints.

Definition of the multi-criteria cost function weights allow operational objectives to be prioritized. The impact of prioritizing operational objectives was apparent in both optimized routes and speeds. When fuel consumption and voyage time are prioritized, the shortest route is no longer attractive as it requires more time in ice, which increases voyage time and fuel consumption.

Expert opinion provided validation of the routes identified through pathfinding and optimization. During the expert validation exercise, the captains adhered to the AIRSS and ZDS regulatory guidelines. The primary route and speeds identified by the captains matched the agent operating under AIRSS with the equal priority cost function weighting.

When voyage time and fuel consumption were prioritized, model results under all approaches align with the routes identified by captains. However, optimized model speeds were lower than those selected by the captains.

In addition to validating results, the captains provided insight into navigational hazards and factors that are not captured under the modelled regulations or route optimization.

It should be recognized that the navigational decision-making of the captains centered on mitigating the risk of structural damage and besetting. The captains favoured routes that decreased time in ice and proximity to severe ice regimes. The captains reduced speed when old ice was present. In contrast, the agent selected routes and speeds that optimized operational implications: minimizing distance, voyage time, and fuel consumption.

POLARIS offers greater flexibility over AIRSS, allowing operation in more severe ice regimes. The captains expressed concern with this operational flexibility. It was demonstrated that POLARIS allows navigation in ice regimes that the captains considered to be beyond the capability of the vessel. A similar argument has been made against AIRSS [23].

Using AIRSS or POLARIS to justify entry into an ice regime in which a vessel has marginal or no capability of operating poses a risk to navigational safety. This is particularly concerning in the presence of multi-year ice, which increases the likelihood of vessel damage [14].

There are factors other than ice that require consideration for safe Arctic navigation. Routes must be selected considering the extent to which regions have been hydrographically surveyed.

Model results showed the agent strategically navigating to avoid severe ice regimes. In reality, routes must be selected with consideration of hydrographic information and vessel draft limitations.

There is an amount of uncertainty associated with the ice conditions reported in an ice chart. Routes must be selected considering the potential for ice drift. Other navigation hazards include deteriorated visibility and regions that experience high ocean currents which can propel ice and increase the risk of vessel damage. Adopting reduced speed under these scenarios is a safe operating practice.

5.6.2. Implications for Arctic maritime regulations and safe navigation

Open water routes are more economical and safer. A shorter route through ice will not necessarily decrease voyage time or fuel consumption, and operating in marginally capable ice regimes is a risk prone practice.

POLARIS, on its own, is insufficient to support safe navigation in ice. It was demonstrated that POLARIS permitted the agent to enter ice conditions that, in the opinion of the captains, was beyond the capability of a PC5 vessel. Operating in ice conditions beyond the capability of the vessel increases the risk of ship-ice damage and ship besetting.

AIRSS is more conservative than POLARIS, yet a similar scenario can occur. An analysis of ice conditions associated with ship-ice damage events showed that damage occurred in ice regimes that produced positive IN values [14].

Limitations of POLARIS and AIRSS have been identified. It must be recognized that these systems are intended to be complementary decision-support tools. Safe Arctic operations requires a competent crew exercising due caution, considering environmental conditions, sea state, visibility, and ship-ice interactions [7]. The Polar Code supports safe operations and risk management through functional requirements for voyage planning, crew competency, communication, and navigational safety, and through adherence to the vessel's Polar Water Operational Manual [7,9,11].

POLARIS and AIRSS provide a convenient method to estimate the nominal risk posed by complex ice regimes. Policy-makers and ship operators must recognize that any number of ice regimes, i.e. combinations of ice types and partial concentrations, can produce the same RIO or IN value. It does not mean the ice regimes pose an equivalent risk of structural damage.

The ZDS, AIRSS, and POLARIS provide different, and potentially contradictory, constraints. It has been argued that allowing the use of multiple operational risk management guidelines offers coastal states and ship operators flexibility in selecting safe operational solutions [9]. Regardless of the guidelines used, seafarers must recognize the limitations of each methodology and exercise due caution to ensure safe navigation in ice.

There is an increased risk associated with inexperienced crews operating in Arctic waters [53]. POLARIS and AIRSS support operational decision-making, but they do not replace a competent and experienced Arctic crew [9,11]. Additional information, complementary operational risk management tools, and a competent crew experienced with operating in ice are necessary to support safe Arctic navigation [11,14].

POLARIS and AIRSS support the use of icebreaker escort to allow navigation in more severe ice regimes. Although icebreaker escort was not modelled in the current study, it was identified during the expert validation exercise as a suitable risk mitigating measure. Additional costs are associated with icebreaker escort and should be considered in evaluating the cost of implementing POLARIS and AIRSS.

The current study demonstrated that POLARIS allows a PC5 vessel to operate in a combined 9/10th concentration of old and thick first-year ice. Expert opinion is that this is beyond the structural capacity vessel. Contact with multi-year ice is the most significant contributor to ship-ice damage events [52].

POLARIS was adopted by the IMO as interim guidance, with the intention to amend the methodology based on experience and feedback [4]. Justifying the modification of RIVs will require evidence of POLARIS allowing operation in severe ice regimes in which the risk of damage is unacceptable, or, alternatively, evidence of POLARIS prohibiting navigation in normal operating conditions [20]. The method presented here provides a convenient means to assess POLARIS against a range of operating conditions and estimate operational implications.

5.6.3. Future work

The methodology has been applied to the case of Arctic shipping. As presented, this is a generalized methodology that may be applied to other, non-Arctic maritime regulations. Future work will investigate application of the method to a broader range of maritime regulations.

The ship performance model adopted for the current study idealizes an ice regime as successive sections of level ice [37]. Operating in partial concentrations of ice produces significantly less resistance than in level ice of the same thickness [19,26].

Associating level ice resistance with partial ice concentrations may lead to over estimates of required power and fuel consumption. The accuracy of estimates of voyage time and fuel consumption requires validation against full-scale voyage data. Further, other existing ship performance and route selection models [28,29,32,38,42,44] can be applied and validated.

Results are sensitive to the modelled ice conditions, Future works includes quantifying this sensitivity and recommendations on how to contend with this sensitivity when evaluating operational implications.

Routes and speeds are identified through multi-criteria optimization. The cost function weight ratio influences the results. The relative importance of each cost function element is dependent not only on the assigned weighting, but also on the units and scale (e.g. km, hours, tonnes). There is no definitive correct weight ratio, rather it is a subjective assignment based on the perspectives of decision-makers and end users of the method.

There exist techniques in the literature to establish multi-criteria weighting schemes [54] and procedures to estimate the relative importance of criteria, such as analytical hierarchy process [55,56]. These methods will be explored in subsequent phases of model development.

The expert validation exercise identified factors that require consideration for safe navigation in ice: hydrographic survey data, vessel draft limitations, high current areas, periods of reduced visibility, sea ice drift, and the use of icebreaker escort. The method can be enhanced by incorporating these elements. Similar conclusions were drawn by Lehtola et al. [57], in which ship captains provided their perspectives on the use of an automated route selection tool.

The uncertainty of reported ice conditions will influence route viability. Incorporating a sea ice drift forecast model [58] could ameliorate the discrepancy between reported and observed ice conditions.

Probabilistic modelling is another approach to dealing with the uncertainty associated with ice (and other) conditions. Dijkstra's shortest-path algorithm is ineffective for pathfinding in stochastic environments. Reinforcement learning approaches will be considered for pathfinding and optimization in stochastic environments.

Specific to marine policy, the method presented here can be used to evaluate the impact that navigating in ice has on ship emissions and support policy-makers in developing effective emission control regulations.

5.7. Conclusion

A methodology for evaluating the operational implications incurred under different maritime regulations was presented. The method combines a ship performance model, regulatory constraints, and multi-criteria pathfinding and optimization. A multi-criteria form of Dijkstra's shortest-path algorithm is employed for pathfinding.

The novelty of the current study is a generalized method that provides policy-makers with a means to evaluate the operational implications associated with maritime regulations and ship owners with a means to assess economic regulatory implementation strategies.

The method was applied to the case of Arctic shipping. The ship performance model provides estimates of operational implications incurred during the voyage: distance, voyage time, and fuel consumption. Approaches for assigning structural safety constraints for ships in ice were modelled following the AIRSS and POLARIS regulatory guidelines, speed limits developed based on a first-principle ship-ice interaction model, and navigation in the absence of structural safety constraints.

Results have implications for Arctic maritime policy and safe and efficient navigation in ice. Open water routes are more economical and safer. POLARIS is the less conservative regulatory guideline, permitting operations in ice conditions in which a vessel has only marginal capability. Compared to AIRSS, POLARIS offers greater flexibility in navigational decision-making, but can increase voyage time, fuel consumption, and the risk of structural damage.

The AIRSS and POLARIS regulatory guidelines are insufficient to ensure safe navigation in ice. AIRSS and POLARIS support operational decision-making, but they do not replace a competent crew experienced in navigating in ice. Additional information and complementary tools are necessary to support safe and efficient Arctic navigation.

Development of the method is ongoing and future work includes modelling and evaluation of other maritime regulations, validation of model results against full-scale voyage data, consideration of alternate ship performance models, and incorporation of additional factors necessary to support decision-making and safe navigation.

Techniques and procedures to establish multi-criteria weight schemes and the relative importance of cost function elements will be investigated in future studies.

Incorporating a sea ice drift forecast model would address concerns with uncertainty in reported ice conditions. Reinforcement learning algorithms can support pathfinding and optimization in a stochastic environment.

The method has potential application beyond Arctic shipping, and can be used to evaluate a broad range of maritime regulations.

5.8. Acknowledgements

The financial support of the Lloyd's Register Foundation is acknowledged with gratitude. Lloyd's Register Foundation helps to protect life and property by supporting engineering-related education, public engagement and the application of research.

5.9. References

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6. DISCUSSION AND CONCLUSION

There were two primary contributions of the thesis: the proposal of a scenario-based Arctic shipping operational risk management framework, and the development of a general method to evaluate the operational implications incurred under maritime regulatory constraints.

The Arctic shipping operational risk management framework extended the POLARIS regulatory guideline to consider consequences of a ship-ice damage event, specifically the potential life-safety consequences of a ship evacuation, and the ecological and socio-economic consequences of an oil spill. Risk-based operating limits were assigned based on the likelihood of ship-ice damage (captured in the existing POLARIS methodology) and the potential consequence severity.

The framework provided a pragmatic approach to link multidisciplinary knowledge and research to inform risk-based decision-making for Arctic shipping at the operational and regulatory levels. The proposed framework was further developed. First, a life-safety consequence model for Arctic ship evacuations was established. Then a method to aggregate the consequences of Arctic ship accidents was developed.

Establishing a life-safety consequence model for Arctic ship evacuations addressed a gap in the body of knowledge related to Arctic maritime risk management. A scenario-based life-safety consequence model was established through expert knowledge elicitation. The consequence model consisted of a conceptual framework of the factors that influence the potential for loss of life during a ship evacuation, and quantified consequence severities for different ship evacuation scenarios.

The Arctic shipping operational risk management framework evaluated a vessel's operational exposure level based on total consequence severity. A method to aggregate consequences and estimate total consequence severity for ship accident scenarios was developed. The consequence aggregation method combined the life-safety consequence model presented in the thesis with an existing environmental consequence model for Arctic marine oil spills. Consequence aggregation was achieved through monetization of consequence severities. A qualitative framework to evaluate total consequence severity was proposed, providing a data-driven and practical procedure for assessing, managing, and communicating Arctic shipping risks.

The other primary contribution of the thesis was the development of a general method for evaluating operational implications associated with Arctic maritime regulations. The study complemented the proposed augmentation of the POLARIS regulatory guideline. The method supports policy-makers in conducting cost-benefit analyses necessary in the development of maritime regulations, and supports Arctic shipping stakeholders in establishing efficient regulatory implementation strategies.

The general method combined a ship performance model, regulatory constraint models, and multi-criteria pathfinding and optimization algorithms. The method was applied to a PC5 vessel navigating the Northwest Passage. The operational implications incurred under the POLARIS and AIRSS regulatory guidelines were evaluated and compared.

6.1. Main findings

It has been demonstrated throughout the thesis that Arctic ship operations pose risks to life-safety, environment, and Arctic stakeholders. The proposed Arctic shipping operational risk management framework provided a risk-based decision-support tool for Arctic ship operations. The proposed framework was developed to be amenable to being adopted and adapted with the existing POLARIS regulatory guideline. POLARIS was augmented such that operating limits for ships in ice are based on the risk profiles of different ship types and regions. Region-specific risk factors included ecological and socio-economic sensitivities and the availability and capacity of SAR resources. The framework was demonstrated for a cruise ship and an oil tanker navigating the coast of Svalbard, Norway.

The life-safety consequence model provided estimates of life-safety consequence severity for Arctic ship evacuation scenarios. Results showed response time and survivability to be the primary factors influencing life-safety consequence severity. Response time was evaluated as having the greatest level of influence on the expected number of fatalities.

Ship type has a significant impact on life-safety consequence severity. High POB passenger vessels, e.g. cruise ships, are the worst-case scenario among evaluated ship types. The increased severity level was attributed to the large numbers of POB exceeding available SAR capacities, and the fact that passengers typically have no experience in evacuation and survival.

In contrast, cargo vessels posed the lowest life-safety consequence severity. This was attributed to the competency and experience of professional seafarers and the requirement for larger commercial vessels to maintain regular reporting with maritime authorities.

The consequence aggregation method was developed to estimate the total consequence severity of an Arctic ship accident scenario, considering life-safety and environmental consequences. The total consequence severity was dependent on ship type and region. Results indicated that ship accidents involving a cruise ship in regions associated with long response times and oil tankers in environmentally sensitive regions are worst-case scenarios, posing similar total consequence severity levels.

The operational implications incurred by a PC5 vessel navigating the Northwest Passage under POLARIS and AIRSS regulatory constraints were evaluated. AIRSS provided a more conservative assessment of vessel capability in ice, relative to POLARIS. AIRSS enforced a binary go/no-go operating criteria, whereas POLARIS allowed the use of reduced speeds in ice regimes in which a vessel had marginal operating capability.

POLARIS offered greater flexibility, but operating in more severe ice regimes required reduced speeds and higher engine power, resulting in increased voyage time and fuel consumption. AIRSS required longer routes to avoid severe ice regimes, but was associated with shorter voyage time and lower fuel consumption. This finding was supported by the expert opinions of Arctic ship captains, who stated that open water routes are more economical and safer.

The method employed multi-criteria optimization for route selection. The defined multi-criteria cost function allowed operational objectives to be prioritized in the selection of optimal routes and speeds. Changing multi-criteria cost function weight ratios resulted in speed adjustments and changes in voyage time and fuel consumption. Results demonstrated that when fuel consumption and voyage time were prioritized, the optimal route and speeds under POLARIS aligned with those under AIRSS.

Main results of the research are summarized in Table 6.1.

Table 6.1. Summary of main results.

Chapter	Results
Ch. 2. A framework for integrating life-safety and environmental consequences into conventional Arctic shipping risk models	• A methodology to assess scenario-based ecological, socio-economic, and life-safety consequence categories for Arctic ship operations. • An operational risk management framework that is intentionally amenable to being adopted and adapted to existing maritime regulations. • Application of the framework to POLARIS for assignment of risk-based operating criteria based on ecological, socio-economic, and life-safety consequence categories.
Ch. 3. Consequence modelling for Arctic ship evacuations using expert knowledge	• A conceptual framework depicting the factors that influence the potential for loss of life resulting from an Arctic ship evacuation. • Response time and survivability are the primary factors influencing consequence severity. • Passenger vessels pose the highest life-safety consequence severity. • The worst-case scenario is an uncontrolled evacuation during winter in severe wind and sea state.
Ch. 4. A consequence aggregation method for Arctic ship accidents	• Based on total consequence severity, worst-case accident scenarios are an oil tanker in an environmentally sensitive region, or a high POB passenger vessel in a region associated with a long response time. • Environmental consequence is the predominant contributor to total consequence severity for oil tankers and bulk carriers. • Total consequence severity for high POB passenger vessels is comprised of appreciable environmental and life-safety consequence levels.
Ch. 5. A method for evaluating the operational implications of regulatory constraints on Arctic shipping	• Compared to AIRSS, POLARIS allows navigation in more severe ice regimes. • Operating in more severe ice regimes requires reduced speeds and higher engine power, resulting in increased voyage time and fuel consumption. • Open water routes allow increased speed at lower engine power, and are thus more economical and safer. • Changing multi-criteria cost function weight ratios results in adjustments to optimized speed resulting in changes in voyage time and fuel consumption.

6.2. Implications for safe and efficient Arctic maritime operations

The implications of the research on safe and efficient Arctic maritime operations are summarized in this section. Implications to Arctic maritime policy and regulation are highlighted.

The Arctic shipping operational risk management framework provided a systematic approach to link multidisciplinary research to inform risk-based decision-making at the operational and regulatory levels. The implication to Arctic maritime operations is that vessels that posed the potential for higher life-safety and environmental consequences were subjected to more conservative operational constraints.

At the regulatory level, the proposed framework could support the risk assessment used in establishing a vessel's Polar Water Operations Manual (PWOM) and Polar Ship Certificate (PSC), required by the Polar Code [1].

The POLARIS methodology was introduced by the IMO as interim guidance, with the expectation to revisit the methodology after it has been in use for several years [2]. The framework proposed here can be seen as a recommended revision to POLARIS.

The life-safety consequence model for Arctic ship evacuations identified response time and survivability as the two primary factors influencing consequence severity. Response time was influenced by proximity of SAR resources and SAR capacity. Survivability was influenced by the suitability of LSAs and the degree of preparedness of those on board for evacuation.

Despite steps taken to improve Arctic SAR services, e.g. the international Arctic SAR agreement [3], there remains a need for continued enhancement of competency, training, and international cooperation for Arctic SAR services to mitigate the life-safety consequence severity posed by Arctic shipping. Arctic cruise operations pose a particularly high life-safety consequence severity [4,5]. There is a need for enhanced governance and regulatory oversight of Arctic cruise operations [6].

The suitability of LSAs and the level of preparedness of those on board for an evacuation were identified as key factors influencing survivability. The majority of Arctic LSAs and PPE do not provide sufficient thermal insulation to support survival for the Polar Code maximum expected time to rescue of not less than five days [7-10]. Further research and development on Arctic LSAs and PPE is necessary to satisfy the functional requirements of the Polar Code.

The influence of preparedness on survivability highlights the importance of trained and experienced crews for Arctic navigation. The Polar Code takes into account the competency of navigational officers but does not consider the risk associated with crews with no Arctic experience. Several Arctic shipping experts held the opinion that the officer navigational training requirements stipulated in the Polar Code have eroded the quality and level of experience of Arctic navigators. Future revision of the Polar Code may consider the requirement for advanced training of all crew, including addressing the increased risk posed by crews with no Arctic experience.

Aggregating consequences allowed Arctic ship accident scenarios to be compared based on total consequence severity. Oil spills have been recognized as the greatest threat facing the Arctic environment [11]. Based on total consequence severity, the current study suggested that mitigating the risks associated with Arctic cruise operations is of near equal priority to that of Arctic tanker operations.

Total consequence severity was dependent on accident location. Effective operational risk management must consider regional characteristics, such as ecological and socio-economic sensitivities and SAR capabilities.

The operational implications incurred under POLARIS and AIRSS were compared. Optimal routes identified through pathfinding and optimization were validated against expert opinion. While POLARIS offers flexibility to operate in more severe ice conditions, it may require reduced speeds and increased engine power which can result in increased voyage time, fuel consumption, and the risk of vessel damage.

The ZDS, AIRSS, and POLARIS are intended to be complementary decision-support tools. Seafarers must recognize the limitations of each methodology and exercise due caution to ensure safe navigation in ice. These regulatory guidelines do not replace a competent and experienced Arctic crew [12,13]. Additional information, complementary operational risk management tools, and a competent crew experienced with operating in ice are necessary to support safe Arctic navigation [13,14].

6.3. Limitations of research and future work

6.3.1. Integrating consequences into Arctic shipping operational risk assessments

The proposed Arctic shipping operational risk management framework integrated consequences into the POLARIS regulatory guideline. Several limitations and areas for future work are acknowledged.

The framework considered potential consequences of a ship accident. Evaluating the likelihood of a ship evacuation or oil spill was out of scope. The framework remains under development. Next steps include calibration of RIV adjustment factors and establishing risk-based operating limits for high consequence scenarios.

Applying the risk management framework to POLARIS linked the potential consequences of an Arctic ship accident solely to ice damage. Other accident types, e.g. groundings, require consideration.

It is recognized that a network of regulations govern Arctic shipping and differentiate risk associated with different ship types, e.g. the Polar Code, SOLAS, MARPOL, and STCW [1,15,16,17]. Incorporating life-safety, ecological, and socio-economic consequences into operational risk management practices requires further consideration of the existing network of maritime regulations.

Stakeholder feedback was collected on the proposed Arctic shipping operational risk management framework. Continued elicitation of feedback is necessary. Relevant stakeholders include ship owners and operators, Arctic communities and other Arctic stakeholders, classification societies, policy-makers, and insurance underwriters.

6.3.2. Life-safety consequence model for Arctic ship evacuations

The life-safety consequence model estimated consequence severity of Arctic ship evacuation scenarios. Evaluating causal factors or the likelihood of an evacuation was out of scope.

The consequence model was scenario-based, with quantified severity indices limited to the nineteen evacuation scenarios defined in the study. Evaluating a broader range of evacuation scenarios is an area for future work.

The majority of expert participants had Canadian Arctic shipping backgrounds. While the results of the study may be most applicable to the Canadian Arctic, effort was made to highlight disparities with the Northern Sea Route and the Baltic Sea.

6.3.3. Aggregating consequences of Arctic ship accidents

Existing models for life-safety and environmental consequence were adopted for the consequence aggregation method.

Life-safety consequence severity of an Arctic ship evacuation was estimated as a function of response time. Response time estimates used in the study assumed the deployment of a single SAR asset [18]. Evaluating the impact that the number and combination of SAR assets would have on response time and life-safety consequence severity was out of scope.

The environmental consequence severity of an Arctic oil spill reflected, in part, the socio-economic value of a region [19]. Socio-economic value in the Canadian Arctic should consider indigenous rights and land and marine uses [20,21]. Expansion of the environmental consequence model to capture indigenous socio-economic impacts is necessary.

Eliciting stakeholder feedback on the consequence aggregation method is an area for future work. Relevant stakeholders include indigenous communities, risk analysis practitioners, seafarers, ship operators, insurance underwriters, and policy-makers.

6.3.4. Evaluating operational implications of Arctic maritime regulations

A general method for evaluating the operational implications of maritime regulations was established. The methodology was applied to the case of Arctic shipping, evaluating the POLARIS and AIRSS regulatory constraints.

It is acknowledged that under Canadian jurisdiction a modified form of POLARIS is enforced. For the purpose of voyage planning, a ship is not permitted to enter an ice regime with a calculated RIO less than zero. Future work will investigate application of the method to a broader range of maritime regulations.

Note that the Arctic shipping operational management framework proposed in this thesis is under development and was not in scope for evaluation of operational implications.

An existing ship performance was adopted. The ship performance model employed an idealization of an ice regime and was selected because it uses conventional ice chart data as input. Other ship performance models and environmental data may be considered.

Safe Arctic navigation in ice requires consideration of many factors. The current study modeled sea ice, open water, and available engine power. Other factors that may be considered include bathymetry, vessel draft limitations, hazardous areas, periods of reduced visibility, sea ice drift, and the use of icebreaker escort [22]. Future revision of the model will investigate incorporation of these factors.

Probabilistic modelling is an approach to dealing with the uncertainty associated with sea ice data and other factors. Dijkstra's shortest-path algorithm is not a practical approach for pathfinding in stochastic environments. Reinforcement learning approaches will be considered for pathfinding and optimization in stochastic environments.

A sensitivity of the multi-criteria cost function weight ratio was presented. While there is no correct weight ratio (i.e. cost function weight ratios must be assigned subjectively by an end-user of the method), there exist techniques and procedures to establish multi-criteria weighting schemes [23,24]. Methods for multi-criteria decision-making will be investigated in future studies.

The method evaluated the operational implications incurred by a ship operator. There are a number of stakeholders impacted by the implementation of maritime regulations. Evaluating the operational implications incurred by other Arctic shipping stakeholders is an area for future work.

6.4. Concluding remarks

The objective of the thesis was to contribute to the management of safe and efficient Arctic maritime operations. There were two primary contributions of the research: a scenario-based Arctic shipping operational risk management framework that integrated consequences into conventional regulatory operational risk assessments, and a general method to evaluate the operational implications of Arctic maritime regulatory constraints.

The proposed Arctic shipping operational risk management framework was developed further. A life-safety consequence model for Arctic ship evacuations was established, and a method to aggregate life-safety and environmental consequences of Arctic ship accidents was developed.

Integrating life-safety, ecological, and socio-economic consequences into an Arctic shipping operational risk management framework contributes to more holistic risk management of Arctic ship operations and enhances the safety of crew and passengers and protection of the Arctic environment and its stakeholders. The framework provides a pragmatic means to link ongoing scientific research with risk-based methods to support decision-making for Arctic shipping at the operational and regulatory levels.

Evaluating the operational implications incurred under Arctic maritime regulations supports evidence-based development of regulations and efficient Arctic ship operations. The general method provides policy-makers, classification societies, and other Artic shipping stakeholders with a tool to evaluate the operational implications associated with maritime regulations and to assess operationally efficient implementation strategies.

6.5. References

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APPENDIX A. PHASE 2 SURVEY QUESTIONS AND EVACUATION SCENARIOS

Survey Block A – Levels of influence

Survey participants were asked to assess factors that influence life-safety consequence severity during an evacuation and rescue in Arctic waters. The level of influence was rated on the five-point Likert scale (Table A.1).

Table A.1. Likert scale for level of influence.

Extreme influence	Major influence	Moderate influence	Slight influence	No influence

Question A1

Considering a ship evacuation in Arctic waters, rate the factors (Table A.2) for their level of influence on the expected number of fatalities.

Table A.2. Factors evaluated for level of influence on expected number of fatalities.

Factors	
Response time (i.e. the time from when an emergency alert is sent to when rescue is complete)	Presence of an accompanying vessel or vessel of opportunity
Number of personnel onboard (POB)	Evacuation in ice covered water
Passengers onboard (as opposed to only seafaring crew)	Evacuation in open water
Crew experienced in Arctic operations	Weather (i.e. wind, sea state, visibility)
SAR capacity	Temperature
Proximity to local communities (e.g. accommodating survivors, local SAR resources)	Time available for evacuation (e.g. controlled evacuation versus rapid/unorganized evacuation)
Suitability of life-saving appliances (e.g. survival suits, life rafts / life boats)	Ability to communicate

Question A2

Considering a ship evacuation in Arctic waters, rate the factors (Table A.3) for their level of influence on response time (i.e. the time from when an emergency alert is sent to when rescue is complete).

Table A.3. Factors evaluated for level of influence on response time.

Weather (i.e. wind, sea state, visibility)
Evacuation in ice covered water
Evacuation in open water
Proximity to SAR resources
SAR capacity
Presence of an accompanying vessel or vessel of opportunity
Ability to communicate
Number of personnel onboard (POB)
Proximity to local communities (e.g. accommodating survivors, local SAR resources)

Question A3

Considering a ship evacuation in Arctic waters, rate the factors (Table A.4) for the level of influence they have on the ability of evacuees to survive until rescue.

Table A.4. Factors evaluated for level of influence on survivability.

Temperature
Weather (i.e. wind, sea state, visibility)
Evacuation in ice covered water
Evacuation in open water
Suitability of life-saving appliances (e.g. survival suits, life rafts / lifeboats)
Crew experienced in Arctic operations
Time available for evacuation (e.g. controlled evacuation versus rapid/unorganized evacuation)
Passengers onboard (as opposed to only seafaring crew)

Survey Block B – Evacuation scenarios

Survey participants were asked to rate the life-safety consequence severity posed by 19 different evacuation scenarios (Table A.5).

Table A.5. Evacuation scenarios.

Scenario	Factors				
	Season	**Ice conditions**	**Wind & sea state**	**Evacuation**	**Response time**
B1 (Baseline)	Summer	Sea ice present	Calm	Controlled	12 hours
B2	Summer	Sea ice present	Calm	Controlled	**24 hours**
B3	Summer	Sea ice present	Calm	Controlled	**2 days**
B4	Summer	Sea ice present	Calm	Controlled	**5 days**
B5	Summer	**Open water**	Calm	Controlled	12 hours
B6	Summer	Sea ice present	**Severe**	Controlled	12 hours
B7	Summer	Sea ice present	Calm	**Rapid/Uncontrolled**	12 hours
B8	Summer	**Open water**	**Severe**	Controlled	12 hours
B9	Summer	**Open water**	Calm	**Rapid/Uncontrolled**	12 hours
B10	Summer	Sea ice present	**Severe**	**Rapid/Uncontrolled**	12 hours
B11	Summer	**Open water**	**Severe**	**Rapid/Uncontrolled**	12 hours
B12	**Winter**	Sea ice present	Calm	Controlled	12 hours
B13	**Winter**	**Open water**	Calm	Controlled	12 hours
B14	**Winter**	Sea ice present	**Severe**	Controlled	12 hours
B15	**Winter**	Sea ice present	Calm	**Rapid/Uncontrolled**	12 hours
B16	**Winter**	**Open water**	**Severe**	Controlled	12 hours
B17	**Winter**	**Open water**	Calm	**Rapid/Uncontrolled**	12 hours
B18	**Winter**	Sea ice present	**Severe**	**Rapid/Uncontrolled**	12 hours
B19	**Winter**	**Open water**	**Severe**	**Rapid/Uncontrolled**	12 hours

APPENDIX B. INTERDISCIPLINARY COMMITTEE ON ETHICS IN HUMAN RESEARCH – APPROVAL LETTER

MEMORIAL UNIVERSITY

Interdisciplinary Committee on
Ethics in Human Research (ICEHR)

St. John's, NL Canada A1C 5S7
Tel: 709 864-2561 icehr@mun.ca
www.mun.ca/research/ethics/humans/icehr

ICEHR Number:	**20210767-EN**
Approval Period:	October 16, 2020 – October 31, 2021
Funding Source:	Lloyd's Register Foundation [RGCS#20192453]
Responsible Faculty:	Dr. Brian Veitch Faculty of Engineering and Applied Science
Title of Project:	*A knowledge elicitation study to inform life-safety consequence modelling for Arctic shipping*

October 16, 2020

Dr. Brian Veitch
Department of Ocean and Naval Architectural Engineering
Faculty of Engineering and Applied Science
Memorial University of Newfoundland

Dear Dr. Veitch:

Thank you for your correspondence addressing the issues raised by the Interdisciplinary Committee on Ethics in Human Research (ICEHR) concerning the above-named research project. ICEHR has re-examined the proposal with the clarification and revisions submitted, and is satisfied that the concerns raised by the Committee have been adequately addressed. <u>However, the finalized survey must be reviewed by ICEHR prior to being used to collect data from your participants. Please submit an **ICEHR Amendment Request form** with the survey once it has been finalized.</u>

In accordance with the *Tri-Council Policy Statement on Ethical Conduct for Research Involving Humans (TCPS2)*, the project has been granted *full ethics clearance* to <u>October 31, 2021</u>. ICEHR approval applies to the ethical acceptability of the research, as per Article 6.3 of the *TCPS2*. Researchers are responsible for adherence to any other relevant University policies and/or funded or non-funded agreements that may be associated with the project.

The *TCPS2* **requires** that you submit an <u>Annual Update</u> to ICEHR before <u>October 31, 2021</u>. If you plan to continue the project, you need to request renewal of your ethics clearance and include a brief summary on the progress of your research. When the project no longer involves contact with human participants, is completed and/or terminated, you are required to provide an annual update with a brief final summary and your file will be closed. If you need to make changes during the project which may raise ethical concerns, you must submit an <u>Amendment Request</u> with a description of these changes for the Committee's consideration prior to implementation. If funding is obtained subsequent to approval, you must submit a <u>Funding and/or Partner Change Request</u> to ICEHR before this clearance can be linked to your award.

All post-approval event forms noted above can be submitted from your Researcher Portal account by clicking the *Applications: Post-Review* link on your Portal homepage. We wish you success with your research.

Yours sincerely,

Kelly Blidook, Ph.D.
Vice-Chair, Interdisciplinary Committee on
Ethics in Human Research

KB/bc
cc: Director, Research Grant and Contract Services

APPENDIX C. REGIONAL ESI RATINGS FOR THE CANADIAN ARCTIC

Regional ESI ratings for the Canadian Arctic were established by WSP for the assessment oil spill risk in Canadian waters [WSP 2014a].

Table C.1. ESI ratings for the Canadian Arctic [WSP 2014] with locations used for the current study.

Sector	Region	ESI	Location in current study
1	Arctic Ocean	1	
2a	Beaufort Sea (West)	4	
2b	Beaufort Sea (East)	2	Amundsen Gulf
3a	High Arctic Islands	1	Viscount Melville Sound, Bathurst Is. (N)
3b	High Arctic Islands	2	Greely Fjord
4	Southwestern Arctic	4	Coronation Gulf
5a	Foxe Basin (South)	1	
5b	Foxe Basin (Central)	1	Foxe Basin
5c	Foxe Basin (North)	3	
6a	Hudson Bay & James Bay (North)	4	Rankin Inlet
6b	Hudson Bay & James Bay (Central)	2	
6c	Hudson Bay & James Bay (South)	5	
7a	Hudson Strait (West)	4	
7b	Hudson Strait (East)	4	
8a	Eastern Arctic (Lancaster Sound)	4	Lancaster Sound
8b	Eastern Arctic (Davis Strait)	3	Davis Strait
8c	Eastern Arctic (Labrador Sea)	2	
9	Mackenzie River & Great Slave Lake	4	

APPENDIX D. RESULT TABLES FOR QUANTITATIVE AGGREGATION METHOD

Table D.1. Quantitative consequence aggregation results by location; Fishing vessel, 10 POB.

	Amundsen Gulf	Coronation Gulf	VMS	Bathurst Is. (N)	Greely Fjord	Lancaster Sound	Foxe Basin	Davis Strait
Spill volume class	1	1	1	1	1	1	1	1
Average spill volume (tonnes)	13	13	13	13	13	13	13	13
Global average spill cost	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31
ESI	2	4	1	1	2	4	1	3
ESI value	2	8	1	1	2	8	1	4
Environmental consequence cost	**0.62**	**2.48**	**0.31**	**0.31**	**0.62**	**2.48**	**0.31**	**1.24**
Average response time (hour) *	20.5	19.0	31.0	34.5	38.0	19.0	21.5	19.5
Severity index value	2.15	2.09	2.45	2.52	2.59	2.09	2.18	2.11
Equivalent fatalities	0.14	0.12	0.28	0.33	0.39	0.12	0.15	0.13
Life-safety consequence cost	**0.42**	**0.37**	**0.84**	**1.00**	**1.18**	**0.37**	**0.46**	**0.39**
Total consequence cost	**1.04**	**2.85**	**1.15**	**1.31**	**1.80**	**2.85**	**0.77**	**1.63**

** Minimum average response time between air- and marine-based estimates*
Costs are in million USD

Table D.2. Quantitative consequence aggregation results by location; Pleasure craft, 10 POB.

	Amundsen Gulf	Coronation Gulf	VMS	Bathurst Is. (N)	Greely Fjord	Lancaster Sound	Foxe Basin	Davis Strait
Spill volume class	1	1	1	1	1	1	1	1
Average spill volume (tonnes)	13	13	13	13	13	13	13	13
Global average spill cost	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31
ESI	2	4	1	1	2	4	1	3
ESI value	2	8	1	1	2	8	1	4
Environmental consequence cost	**0.62**	**2.48**	**0.31**	**0.31**	**0.62**	**2.48**	**0.31**	**1.24**
Average response time (hour) *	20.5	19.0	31.0	34.5	38.0	19.0	21.5	19.5
Severity index value	2.02	1.97	2.33	2.41	2.48	1.97	2.06	1.99
Equivalent fatalities	0.11	0.09	0.21	0.26	0.30	0.09	0.11	0.10
Life-safety consequence cost	**0.32**	**0.28**	**0.64**	**0.77**	**0.91**	**0.28**	**0.34**	**0.29**
Total consequence cost	**0.94**	**2.76**	**0.95**	**1.08**	**1.53**	**2.76**	**0.65**	**1.53**

** Minimum average response time between air- and marine-based estimates*
Costs are in million USD

Table D.3. Quantitative consequence aggregation results by location; Bulk carrier, 25 POB.

	Amundsen Gulf	Coronation Gulf	VMS	Bathurst Is. (N)	Greely Fjord	Lancaster Sound	Foxe Basin	Davis Strait
Spill volume class	4	4	4	4	4	4	4	4
Average spill volume (tonnes)	2,670	2,670	2,670	2,670	2,670	2,670	2,670	2,670
Global average spill cost	7.03	7.03	7.03	7.03	7.03	7.03	7.03	7.03
ESI	2	4	1	1	2	4	1	3
ESI value	2	8	1	1	2	8	1	4
Environmental consequence cost	**14.06**	**56.26**	**7.03**	**7.03**	**14.06**	**56.26**	**7.03**	**28.13**
Average response time (hour) *	20.5	19.0	31.0	34.5	38.0	19.0	21.5	19.5
Severity index value	1.86	1.80	2.22	2.31	2.39	1.80	1.90	1.82
Equivalent fatalities	0.07	0.06	0.17	0.20	0.25	0.06	0.08	0.07
Life-safety consequence cost	**0.22**	**0.19**	**0.50**	**0.61**	**0.74**	**0.19**	**0.24**	**0.20**
Total consequence cost	**14.28**	**56.45**	**7.53**	**7.64**	**14.81**	**56.45**	**7.27**	**28.33**

** Minimum average response time between air- and marine-based estimates*
Costs are in million USD

Table D.4. Quantitative consequence aggregation results by location; Oil tanker, 25 POB.

	Amundsen Gulf	Coronation Gulf	VMS	Bathurst Is. (N)	Greely Fjord	Lancaster Sound	Foxe Basin	Davis Strait
Spill volume class	5	5	5	5	5	5	5	5
Average spill volume (tonnes)	8,900	8,900	8,900	8,900	8,900	8,900	8,900	8,900
Global average spill cost	14.30	14.30	14.30	14.30	14.30	14.30	14.30	14.30
ESI	2	4	1	1	2	4	1	3
ESI value	2	8	1	1	2	8	1	4
Environmental consequence cost	**28.60**	**114.37**	**14.30**	**14.30**	**28.60**	**114.37**	**14.30**	**57.19**
Average response time (hour) *	20.5	19.0	31.0	34.5	38.0	19.0	21.5	19.5
Severity index value	1.86	1.80	2.22	2.31	2.39	1.80	1.90	1.82
Equivalent fatalities	0.07	0.06	0.17	0.20	0.25	0.06	0.08	0.07
Life-safety consequence cost	**0.22**	**0.19**	**0.50**	**0.61**	**0.74**	**0.19**	**0.24**	**0.20**
Total consequence cost	**28.81**	**114.56**	**14.79**	**14.91**	**29.33**	**114.56**	**14.54**	**57.38**

** Minimum average response time between air- and marine-based estimates*
Costs are in million USD

Table D.5. Quantitative consequence aggregation results by location; Passenger vessel, 250 POB.

	Amundsen Gulf	**Coronation Gulf**	**VMS**	**Bathurst Is. (N)**	**Greely Fjord**	**Lancaster Sound**	**Foxe Basin**	**Davis Strait**
Spill volume class	3	3	3	3	3	3	3	3
Average spill volume (tonnes)	512	512	512	512	512	512	512	512
Global average spill cost	2.66	2.66	2.66	2.66	2.66	2.66	2.66	2.66
ESI	2	4	1	1	2	4	1	3
ESI value	2	8	1	1	2	8	1	4
Environmental consequence cost	**5.31**	**21.25**	**2.66**	**2.66**	**5.31**	**21.25**	**2.66**	**10.63**
Average response time (hour) *	89.5	44.5	31.0	144.5	142.5	19.0	88.0	33.5
Severity index value	3.62	3.01	2.70	4.03	4.02	2.28	3.60	2.77
Equivalent fatalities	4.14	1.03	0.50	10.74	10.45	0.19	4.01	0.59
Life-safety consequence cost	**12.43**	**3.10**	**1.51**	**32.22**	**31.34**	**0.57**	**12.02**	**1.76**
Total consequence cost	**17.74**	**24.35**	**4.17**	**34.88**	**36.65**	**21.82**	**14.67**	**12.39**

** Average marine-based response time estimates*
Costs are in million USD

Table D.6. Quantitative consequence aggregation results by location; Passenger vessel, 1000 POB.

	Amundsen Gulf	**Coronation Gulf**	**VMS**	**Bathurst Is. (N)**	**Greely Fjord**	**Lancaster Sound**	**Foxe Basin**	**Davis Strait**
Spill volume class	4	4	4	4	4	4	4	4
Average spill volume (tonnes)	2,670	2,670	2,670	2,670	2,670	2,670	2,670	2,670
Global average spill cost	7.03	7.03	7.03	7.03	7.03	7.03	7.03	7.03
ESI	2	4	1	1	2	4	1	3
ESI value	2	8	1	1	2	8	1	4
Environmental consequence cost	**14.06**	**56.26**	**7.03**	**7.03**	**14.06**	**56.26**	**7.03**	**28.13**
Average response time (hour) *	89.5	44.5	31.0	144.5	142.5	19.0	88.0	33.5
Severity index value	4.13	3.56	3.27	4.51	4.50	2.88	4.11	3.34
Equivalent fatalities	13.35	3.66	1.87	32.41	31.59	0.76	12.94	2.16
Life-safety consequence cost	**40.05**	**10.98**	**5.62**	**97.24**	**94.76**	**2.27**	**38.82**	**6.49**
Total consequence cost	**54.12**	**67.24**	**12.66**	**104.27**	**108.83**	**58.53**	**45.85**	**34.62**

** Average marine-based response time estimates*
Costs are in million USD

APPENDIX E. WMO SEA ICE NOMENCLATURE AND MODELLED ICE PROPERTIES

Table E.1. WMO ice type nomenclature and modelled ice thicknesses.

WMO description	WMO code	WMO thickness range	Modeled thickness (m)
New	1	< 10 cm	0.1
Nilas	2	< 10 cm	0.1
Young	3	10 – 30 cm	0.3
Grey	4	10 – 15 cm	0.15
Grey-white	5	15 – 30 cm	0.3
First-year (FY)	6	> 30 cm	0.75
Thin FY	7	30 – 70 cm	0.7
Thin FY – First stage	8	30 – 50 cm	0.5
Thin FY – Second stage	9	50 – 70 cm	0.7
Medium FY	1•	70 – 120 cm	1.2
Thick FY	4•	> 120 cm	2
Old	7•	-	3
Second-year	8•	-	2.5
Multi-year	9•	-	3

Table E.2. WMO ice type nomenclature and AIRSS IM values and POLARIS RIVs for PC5.

WMO description	WMO code	IM for PC5 (CAC 4)	RIV for PC5
New	1	2	3
Nilas	2	2	3
Young	3	2	3
Grey	4	2	3
Grey-white	5	2	3
First-year (FY)	6	2	2
Thin FY	7	2	2
First stage thin FY	8	2	2
Second stage thin FY	9	2	2
Medium FY	1•	2	1
Thick FY	4•	1	0
Old	7•	-4	-2
Second-year	8•	-2	-1
Multi-year	9•	-4	-2
Ice of land origin	Δ•	N/A	N/A
Undetermined	X•	N/A	N/A

Table E.3. WMO ice floe nomenclature and modelled floe sizes.

WMO description	WMO width range	WMO code	Modeled floe size
Pancake	-	0	N/A
Small ice cake, brash	< 2 m	1	N/A
Ice cake	2 – 20 m	2	25 m
Small floe	20 – 100 m	3	100 m
Medium floe	100 – 500 m	4	200 m
Big floe	500 – 2,000 m	5	200 m
Vast floe	2 – 10 km	6	200 m
Giant floe	> 10 km	7	200 m
Fast ice	-	8	N/A
Icebergs, growlers	-	9	N/A
Undetermined	-	X	N/A

APPENDIX F. CALCULATION OF AGGREGATED COST OF GRID STEP

Calculation of the aggregated cost for each grid step in a simplified scenario using a 3 × 3 grid is demonstrated. The agent occupies the centre grid cell and the eight neighbouring cells are modelled with ice regimes and open water (Figure B.1). The ice regime egg codes are borrowed from those presented in the case study.

The agent is modelled as a PC5 vessel operating under POLARIS structural safety constraints. Egg code data and calculated POLARIS RIO and structural safety constraints are presented in Table B.1.

Steps to calculate the aggregated cost to travel to each of the eight neighbouring cells is presented in Table B.2. The optimal speed is identified using the *argmin* function. Voyage time and fuel consumption are calculated using the ship performance model (Section 5.4.1). Aggregated cost of each grid step is calculated using the multi-criteria cost function (Section 5.4.3). A cost function weight ratio for [k, m, l] or [1, 1, 10] is assumed.

Ice regime F produces an RIO value of 18, and entry into the grid cell is prohibited. Ice regime U4 produces an RIO value of 9, and a speed limit of 2.5 m/s is imposed. With a cost function weight ratio [k, m, l] of [1, 1, 10], the lowest aggregated cost grid step is to open water (OW).

Note, this simplified scenario does not demonstrate Dijkstra's shortest-path and the agent may not choose to travel to grid cell OW. The selected path would depend on the location of the designated arrival point.

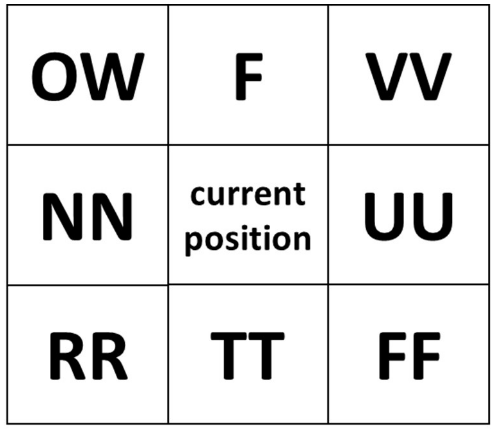

Figure F.1. Simplified 3 × 3 grid with the agent occupying centre grid cell.

Table F.1. Egg code data, POLARIS RIO, and structural safety constraints.

Ice regime	Partial concentration				WMO ice type			POLARIS RIV				POLARIS RIO	Constraint
	a	b	c	OW	a	b	c	a	b	c	OW		
OW	-	-	-	10	-	-	-	-	-	-	3	30	Normal
F	9	1	-	-	7D	4D	-	-2	0	-	-	-18	Prohibited
U1	2	1	-	7	7D	4D	-	-2	0	-	3	17	Normal
U2	5	1	2	2	7D	4D	1	-2	0	3	3	2	Normal
FF	3	1	3	3	7D	4D	1	-2	0	3	3	12	Normal
U4	6	3	-	1	7D	4D	-	-2	0	-	3	-9	Speed limit
RR	2	-	-	8	7D	-	-	-2	-	-	3	20	Normal
NN	5	-	-	5	7D	-	-	-2	-	-	3	5	Normal

Table F.2. Calculation of aggregated cost of each grid step.

Ice regime	Optimized speed				Distance (km)	Voyage time (hr)	Fuel consumption (tonnes)	Aggregated cost of grid step
	a	b	c	OW				
OW	-	-	-	6.5	11.3	0.48	0.18	13.6
F	-	-	-	-	8.0	-	-	+∞
U1	1.0	1.0	-	6.5	11.3	1.28	1.49	27.5
U2	1.0	1.0	6.5	6.5	8.0	1.47	2.00	29.4
FF	1.0	1.0	6.5	6.5	11.3	1.55	1.96	32.5
U4	1.0	1.0	-	2.5	8.0	2.09	2.89	39.0
RR	1.0	-	-	6.5	11.3	1.02	1.05	22.9
NN	1.0	-	-	6.5	8.0	1.28	1.67	26.0