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A method for evaluating operational implications of regulatory constraints on Arctic shipping

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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.

1. 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

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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.

1.1. 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.

1.1.1. 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].

1.1.2. 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. 1).

$$\mathrm{IN} = \sum_{i} \mathrm{IM}_i \times \mathrm{C}_i \tag{1}$$

where IM_i is the IM value of the i^{th} 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].

1.1.3. 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. 2). POLARIS RIO values and RIVs are analogous, but not equal, to AIRSS IN and IM values, respectively.

$$\mathrm{RIO} = \sum_{i} \mathrm{RIV}_i \times \mathrm{C}_i \tag{2}$$

where RIV_i is the RIV of the i^{th} 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 $\geq$0, ‘Elevated operational risk’ for $-10 \leq$ 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.

1.2. 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. 10/10th 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.

1.3. 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.

1.4. 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.

1.4.1. 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].

Table 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 guidelines. Proximity to shoreline.	✔	✖	Dijkstra's	✔	✔	✖
Liu et al. 2016	✖	✖	AIRSS guidelines.	✔	✖	Dijkstra's	✖	✔	✖
Current study	✔	✔	AIRSS guidelines. POLARIS guidelines. Speed limits based on structural analysis.	✔	✔	Multi-criteria Dijkstra's	✔	✔	✔

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.

1.4.2. 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 1. There are several novelties of the current study.

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.

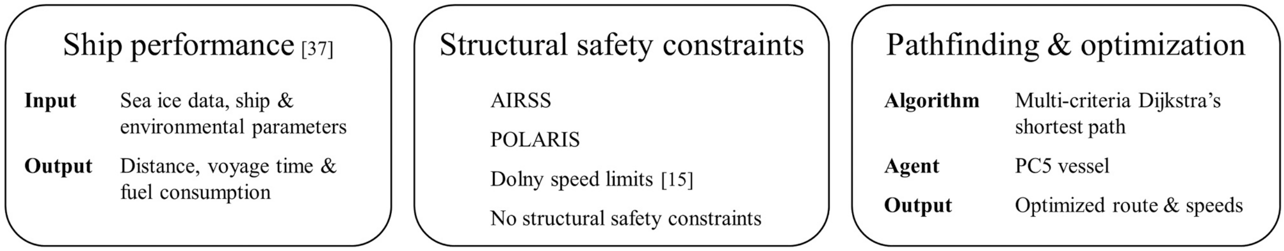

Fig. 1. Elements of the method applied to Arctic shipping.

Table 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			

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.

2. 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 Fig. 1 and detailed in Sections 2.1 to 2.3. The expert validation exercise is discussed in Section 2.4.

2.1. 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 2.

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. 3), ice resistance normalized for a speed of 1 m/s (Eq. 4), and added ice resistance for speeds above 1 m/s (Eq. 5). Total resistance is the sum of the three components (Eq. 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 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. (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. 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.

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 A (Table A.1). Floe size is not considered in the

Table 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**

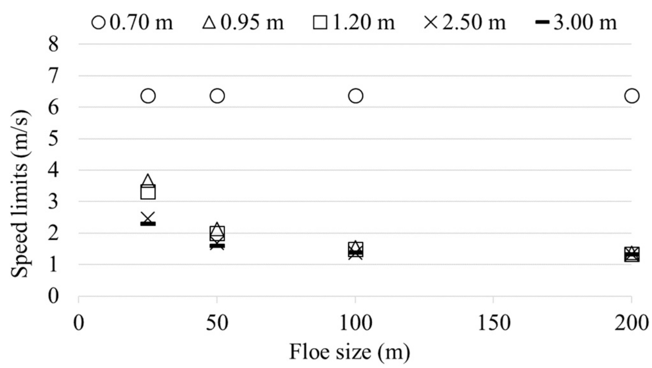

Fig. 2. Speed limits with increasing floe size for a range of ice thickness values (modified from Dolny [15]).

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 Eqs. (3)–(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).

$$R_{OW} = (\rho_w LBDC_b)^{1.1}\left(0.025\left(V/\sqrt{gl}\right) + 8.8\left(V/\sqrt{gl}\right)^5\right)/1000 \tag{3}$$

$$R_{ice} = 0.015(HC)(SAL)B^{0.7}L^{0.2}D^{0.1}h^{1.5}(1 - 0.0083(T+30)) \times \left(0.63 + 0.00074\sigma_f\right)\left(1 + 0.0018(90-\gamma)^{1.6}\right)\left(1 + 0.003(\beta-5)^{1.5}\right) \tag{4}$$

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

$$R_{Total} = R_{OW} + R_{ice} + R_{ice}(V > 1\text{m/s}) \tag{6}$$

$$P = T/0.8(0.122 - 0.0057V) \tag{7}$$

$$fuel \quad consumption = FCR \times P \times t \tag{8}$$

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 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.

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 2.3.

2.2. 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. (1).

If IN ≥ 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. (2).

If RIO ≥ 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 A (Table A.2).

Table 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

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 (Fig. 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 A (Table A.3).

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 4.

2.3. 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 Fig. 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. 9).

$$\begin{aligned} W(U, U', V) &= k \times \text{distance}(U, U') \\ &+ m \times \text{voyage time}(U, U', V) \\ &+ l \times \text{fuel consumption}(U, U', V) \end{aligned} , \tag{9}$$

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 $\sqrt{(2)}$ 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

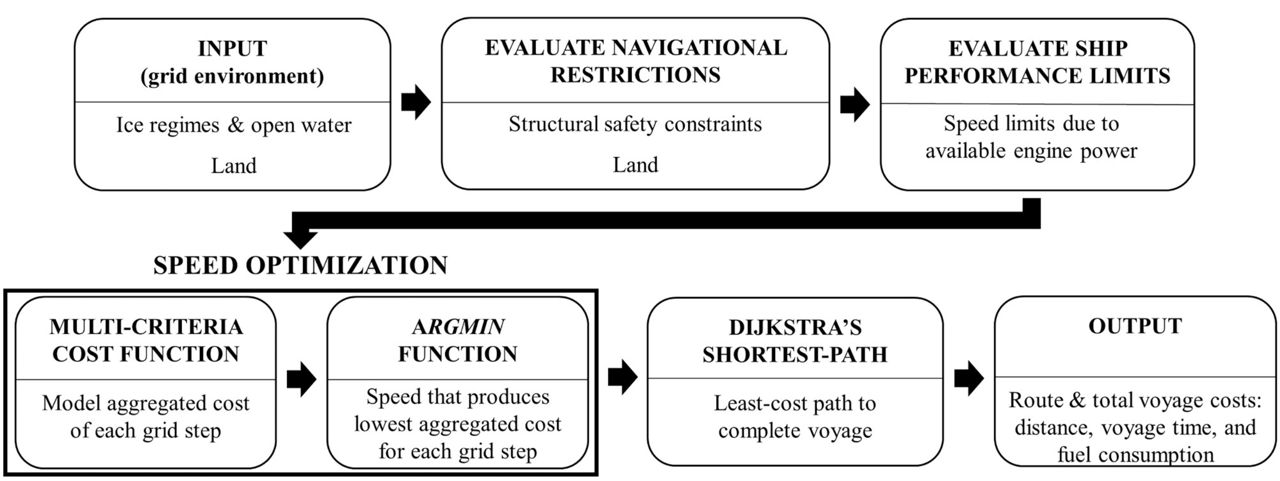

Fig. 3. General framework for pathfinding and optimization.

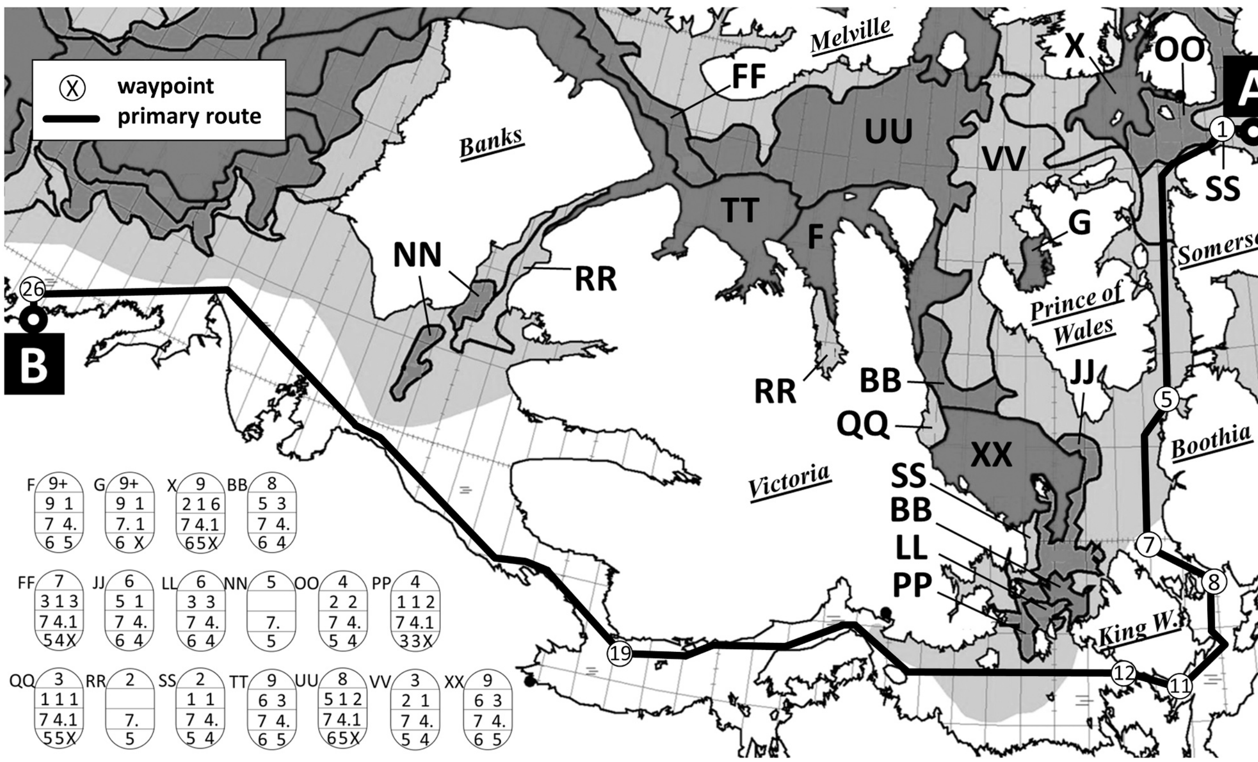

Fig. 4. Optimal route; AIRSS; cost function weights: [1, 1, 1].

Table 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

(Section 2.2). 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 2.1).

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. 10). Available speeds range from 0.5 to 10 m/s in half integer increments.

$$V^* = \underset{V}{\operatorname{argmin}} W(U, U', V) \tag{10}$$

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 B.

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.

2.4. Elicitation of expert opinion

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.

3. 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 3.1.1 to Section 3.1.3). Results of the expert validation exercise are presented in Section 3.2.

3.1. Model results

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

The first set of results used an equal weighting for [distance, voyage

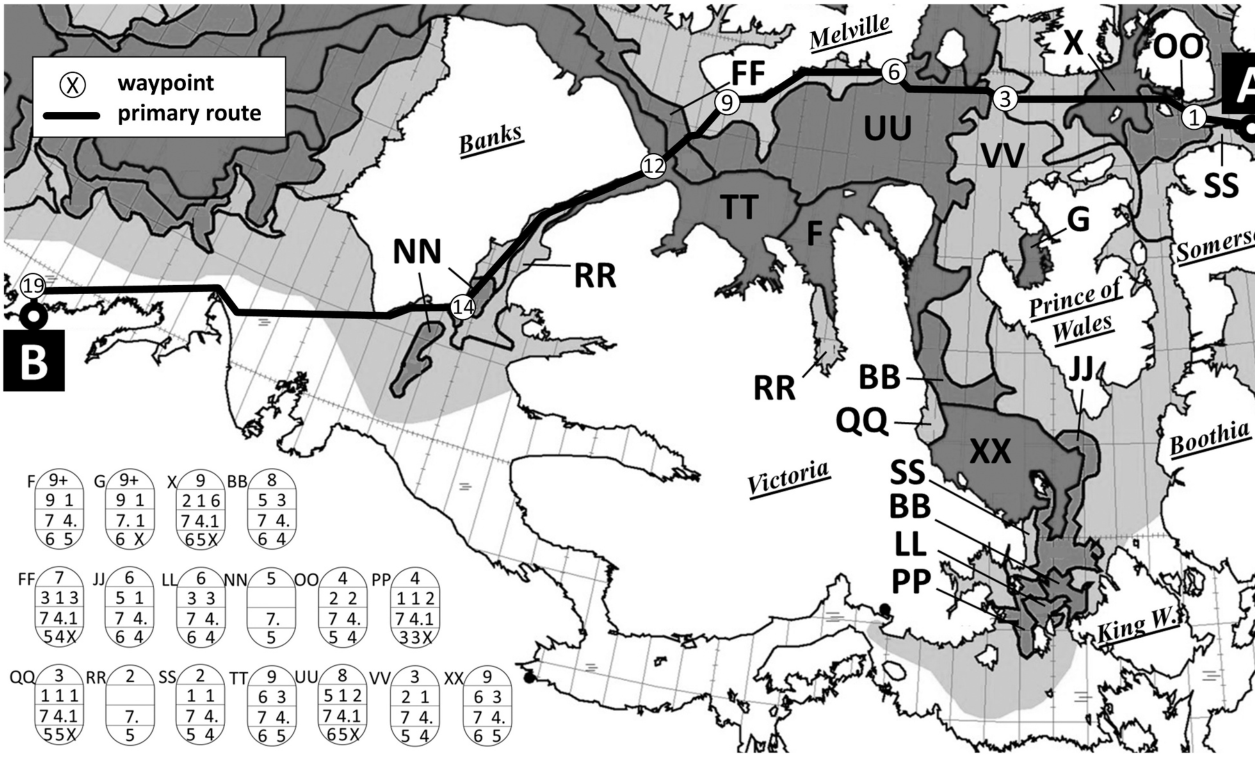

Fig. 5. Optimal route; POLARIS; cost function weights: [1, 1, 1].

time, fuel consumption] of [1, 1, 1]. The optimal route under AIRSS is presented in Fig. 4. The operational implications are presented in Table 5, with each ice regime and section of open water presented separately.

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 1–5) 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 12–26.

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 Fig. 5. Operational implications along the route are presented in Table 6.

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

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.

Table 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

3.1.2. 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 (Fig. 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 7.

Table 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 Fig. 6 and operational implications in Table 8. It is distinctly different than the POLARIS route under the equal weighting [1, 1, 1].

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 10–12), 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.

Table 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

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 12–31).

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 2/10th 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.

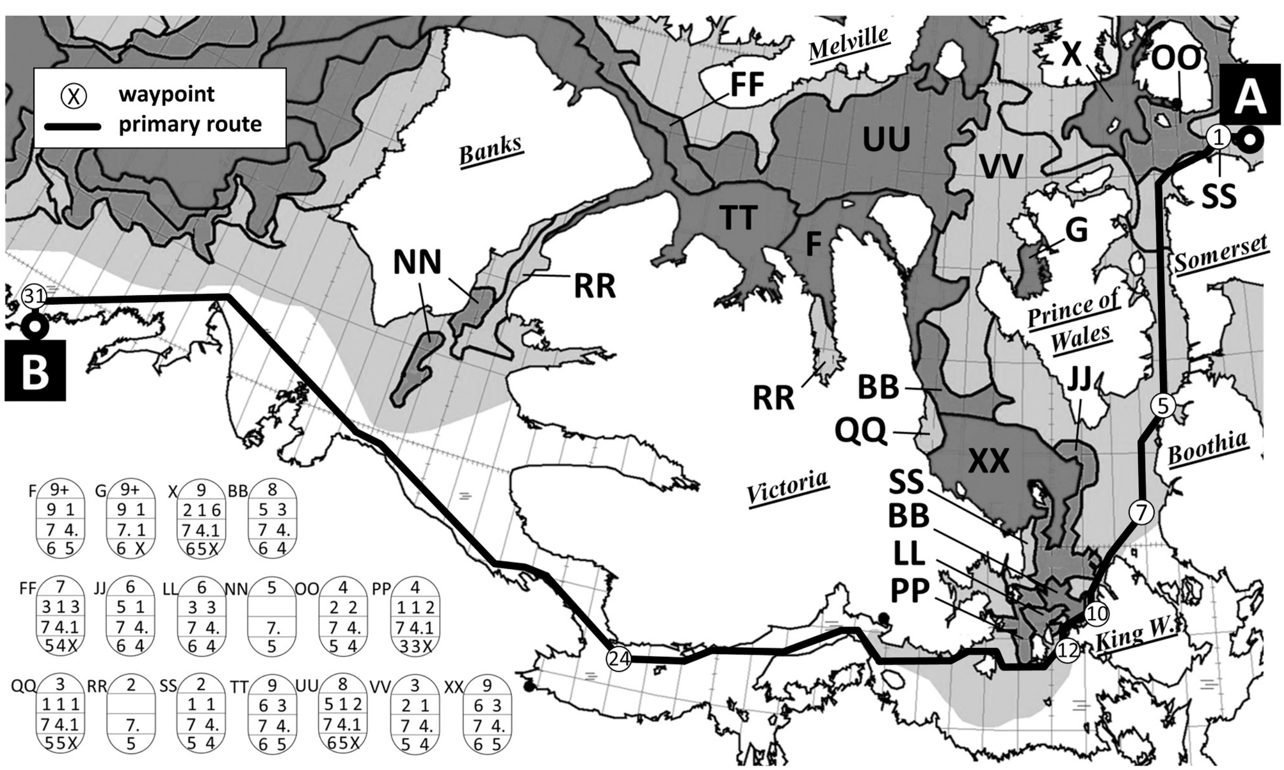

Fig. 6. Optimal route; POLARIS; cost function weights: [1, 1, 10].

3.1.3. 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 (Fig. 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 9, [1, 1, 10] in Table 10, and [1, 10, 100] in Table 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].

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.

Table 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 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 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

This reflects the increased weight of 100 applied to fuel consumption.

3.2. 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 3.2.1. Navigational hazards and ancillary issues raised by the captains are discussed in Section 3.2.2.

3.2.1. Selected routes

Primary and alternate routes are presented in Fig. 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.

The primary route is through Peel Sound, waypoints 1–4. Ice regimes SS and OO produce positive IN values, allowing navigation in the region. Despite positive IN values, a reduced speed of 2.6–3.6 m/s (5–7 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 8–9). 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 9–20). 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 2.6–3.6 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 1.5–2.1 m/s (3–4 knots), depending on the width of the channel created by the icebreaker.

3.2.2. Navigational hazards and ancillary issues

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

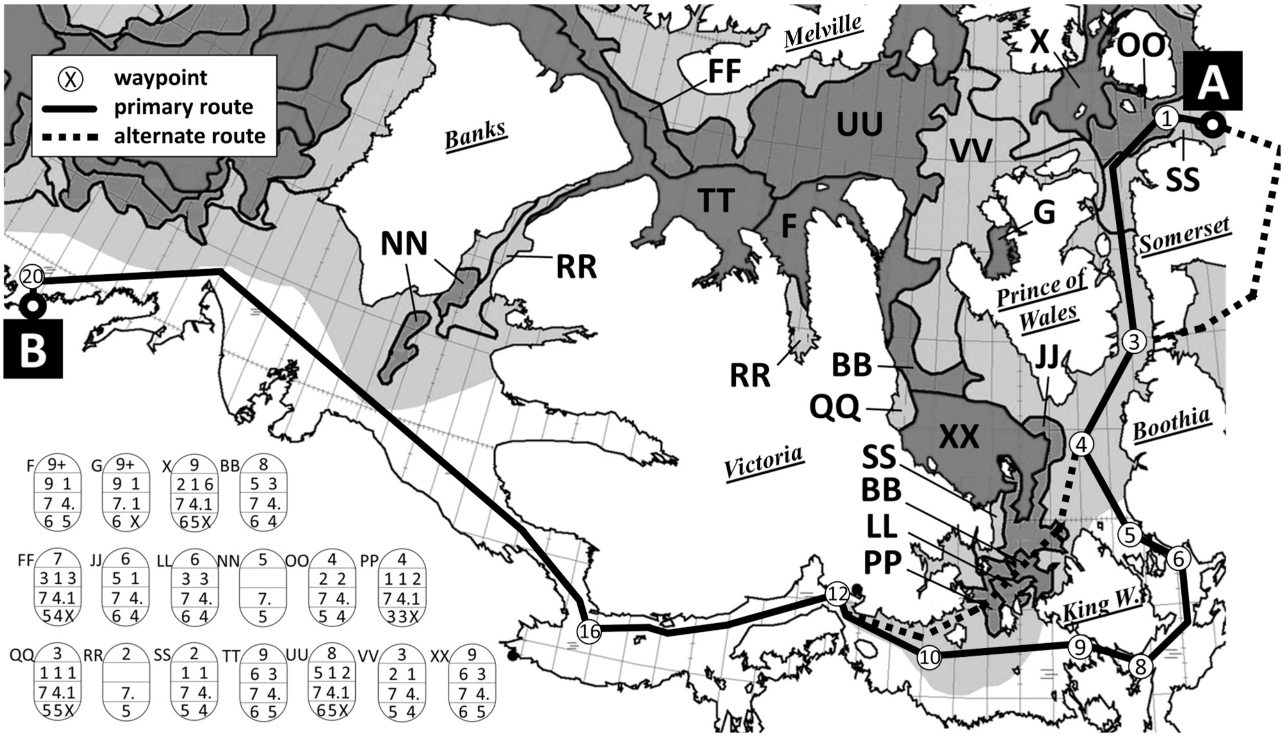

Fig. 7. Primary and alternate routes identified through expert opinion.

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 ($IN \geq 0$), 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.

4. Discussion

4.1. 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.

4.2. 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 complimentary 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.

4.3. 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. 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.

CRediT authorship Contribution statement

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

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Appendix A. WMO sea ice nomenclature and modeled ice properties

See Appendix Table A1–A3.

Table A1
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 A.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 A.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 – 2000 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 B. . Calculation of aggregated cost of grid step

See Appendix Fig. B1.
See Appendix Tables B1 and B2.
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 2.1). Aggregated cost of each grid step is calculated using the multi-criteria cost function (Section 2.3). 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.

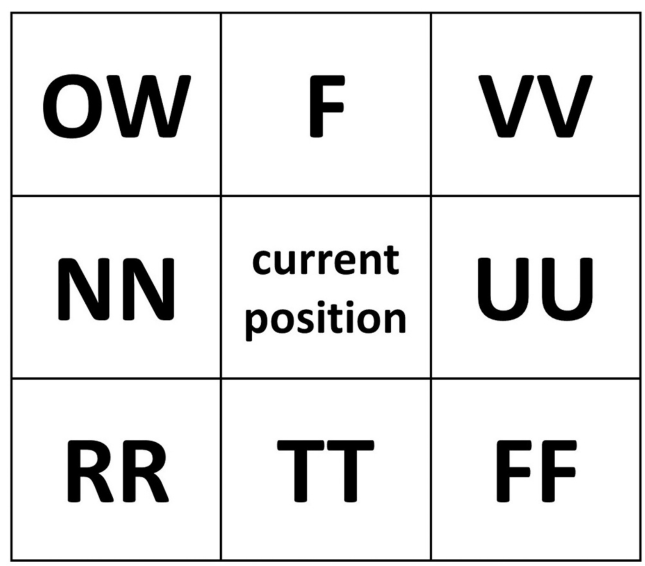

Fig. B.1. Simplified 3 × 3 grid with the agent occupying the centre grid cell.

Table B.1
Egg code data, POLARIS RIO, and structural safety constraints.

Ice regime	Partial concentration				WMO ice type			POLARIS RIV				POLARIS RIO	Structural safety constraint
	a	b	c	OW	a	b	c	a	b	c	OW		
OW	–	–	–	10	–	–	–	–	–	–	3	30	Normal operations
F	9	1	–	–	7D	4D	–	-2	0	–	–	-18	Prohibited entry
U1	2	1	–	7	7D	4D	–	-2	0	–	3	17	Normal operations
U2	5	1	2	2	7D	4D	1	-2	0	3	3	2	Normal operations
FF	3	1	3	3	7D	4D	1	-2	0	3	3	12	Normal operations
U4	6	3	–	1	7D	4D	–	-2	0	–	3	-9	Speed limit (2.5 m/s)
RR	2	–	–	8	7D	–	–	-2	–	–	3	20	Normal operations
NN	5	–	–	5	7D	–	–	-2	–	–	3	5	Normal operations

Table B.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	–	–	$+\infty$
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

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