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Route optimization for vessels in ice: Investigating operational implications of the carbon intensity indicator regulation

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ABSTRACT

The International Maritime Organization has adopted the Carbon Intensity Indicator (CII) regulation to promote decarbonization of shipping operations. The CII regulation includes specific treatment for vessels sailing in ice, which allows the time spent in ice, the associated emissions and transport work, to be excluded from the reported annual CII. The current study investigates the implications and possible side effects of this exemption in all ice-covered waters. A proposed model integrates the CII regulation into a route optimization tool for vessels in ice. The research decomposes the regulation from evaluating an annual CII value to monitoring an instantaneous CII value over a unit distance. A ship performance model is used to estimate resistance, powering, and fuel consumption. A graph-based pathfinding method is applied to find optimal routes and speeds for the vessel. A hypothetical bulk carrier with ice class 1A Super operating in the Canadian Arctic is considered as a case study. The Polar Operational Limit Assessment Risk Indexing System is applied to promote safe operations in ice. The demonstrations explore route optimization with and without CII considerations, including the exemption for ships sailing ice. The results show that the CII regulation promotes reduced speeds to curb fuel consumption and carbon emissions. The findings also indicate that the exemption for sailing in ice conditions influences routing decisions with results that are contrary to the intent of the regulation. This research provides a tool to support ship operators with voyage planning and policy-makers in evaluating the impact of the CII regulation.

1. Introduction

Voyage planning is critical for safe and efficient ship operations. It is a requirement adopted by the International Maritime Organization (IMO) for the shipping industry to ensure safety at sea for vessels and crews, maintain operational efficiency, and protect the environment, according to the guidelines for voyage planning [1]. Voyage planning for Arctic ship operations requires additional considerations regarding the potential risk associated with the route. Operators must evaluate statistical information on ice conditions, the hydrographic data, the supporting capability of coast guard or other escort vessels, and national and international regulations as prescribed by the Polar Code [2]. The current study focuses on voyage planning for vessels adhering to Polar Operational Limit Assessment Risk Indexing System (POLARIS) and the Carbon Intensity Indicator (CII) regulations.

Route optimization tools for vessels are helpful for voyage planning through ice. The tools can generate an optimal route from point A to point B, given the inputs, such as a map with ice information, the objective set for the optimization, and operational constraints. A literature review on route optimization for vessels in ice-covered water shows that the current optimizing models focus more on safety and economic factors [3]. Route optimization tools need to consider carbon emission constraints as an additional factor toward a sustainable solution for shipping operations. Zhang et al. [4] use the Energy Efficiency Operational Indicator (EEOI) [5] as the objective for route optimization in ice. EEOI is similar to a carbon intensity indicator, but the application of EEOI by Zhang et al. [4] differs from the CII regulation requirements. A recent study combines a ship performance model and voyage optimization algorithms to investigate the economic feasibility of Arctic and non-Arctic routes using cost-benefit analysis. However, ship emissions on routing is not considered [6]. Cheaitou et al. [7] integrate a carbon emission tax into an economic and environmental analysis of the Northern Sea Route, but the study does not consider the CII regulation.

Route optimization tools for shipping in ice can also be used to

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investigate the implications of maritime regulations. The regulatory constraint affects navigational decisions and changes the outcome of the optimal route of the voyage. Route optimization tools play a role in predicting the impact of regulatory constraints on operations. For example, Browne et al. [8] illustrated the evaluations of three different regulatory constraints of safe navigation in ice using a specific scenario, including POLARIS, the Arctic Ice Regimes Shipping System (AIRSS), and speed limits. The current study analyzes the implication of the CII regulation for Arctic shipping.

Decarbonization is a significant challenge facing the maritime industry. The IMO adopted the Carbon Intensity Indicator regulatory framework in January 2023, requiring vessels to be operated with improved energy efficiency and reduce carbon emissions [9]. Under the CII regulation, a vessel must report a yearly CII value, estimated as the total mass of carbon dioxide emitted divided by the total transport work in a calendar year. The regulation stipulates required CII values based on ship type and size. If an attained CII value of a vessel does not meet the published requirement, the ship's owner must develop and implement plans to improve the vessel's energy efficiency and further reduce carbon emissions.

Ship owners can control the attained CII value of a vessel in several ways. Operational and design measures to reduce carbon emissions can be implemented, effectively reducing the numerator in the CII formula. Measures may include adopting efficient vessel speeds to reduce fuel consumption [10], switching to alternative low-carbon fuels [11], and design changes to improve vessel performance. Operators may also strategically increase the transport work of the vessel, effectively increasing the denominator of the CII formula and thus decreasing the attained CII value. It is anticipated that operational implications will be associated with implementing the CII regulation, some of which may contradict the objective of the regulation, which is to reduce emissions [12]. This study introduces an approach to integrate CII regulation compliance into the route optimization tool.

The CII regulation includes specific treatment for ships sailing in ice. The periods when ice-classed vessels are sailing in ice conditions are excluded from the CII calculation. The objective of the current study is to investigate the operational implications of the CII regulation for ships sailing in and near ice. The graph-based route optimization method introduced by Browne et al. [8] is adopted for the study. The route optimization tool is a computer-based simulation in which a virtual ship navigates a digital environment and identifies optimal routes and speeds along the route. The digital environment is modelled from published ice charts discretized to grid cells. The method combines a ship performance model, regulatory constraint models, and pathfinding and optimization algorithms. The ship performance model estimates resistance, powering, and associated fuel consumption in open water and ice, and defines vessel performance limitations. The regulatory constraint models include the CII regulation and the POLARIS regulation. Several studies analyzed and applied POLARIS as a safety guideline for operations in the Arctic region [7,8,13]. The pathfinding method is Dijkstra's algorithm, with the cost function being the aggregated sum of the operational objectives. Carbon emissions are based on the vessel's estimated fuel consumption, using conversion rates for specific fuel types defined in the CII regulation.

The reported CII value of a vessel is usually measured on a yearly basis. For this study, an instantaneous CII value is calculated in each traversal of the digital environment through which the vessel transits. The instantaneous CII value is a function of vessel speed and resistance, and thus fuel consumption and emissions, and the grid cell distance. Based on the estimated resistance and fuel consumption in open water and in different ice conditions, speed limits can be imposed to ensure the calculated instantaneous CII value does not exceed the required CII value stipulated in the regulation. The current study also models and adheres to the POLARIS guidelines for safe operations in ice, which prohibits entry into ice conditions that are beyond a ship's structural safety threshold.

Case studies are presented for a hypothetical bulk carrier with ice class 1A Super transiting from Arctic Bay, Nunavut through Baffin Bay in the Canadian Arctic. The case studies examine several proposed modifications to the CII regulation to investigate how the CII regulation and potential changes may impact vessel operations in ice. Although the specific route in the Canadian Arctic is demonstrated, the current approach can be expanded to other ice-covered waters. The contribution of this study is demonstrating a tool that can support voyage planning with adherence to the requirements of the CII regulation. To the best of our knowledge, this work is the first research focusing on route optimization for vessels in ice adhering to CII regulation. This study also provides a means for regulators to review the impact of potential changes to the CII regulation, and to explore how the regulation might incentivize unintended types of operations that increase emissions, decrease safety, or both.

The current study is conducted with some limitations. The ice environment used in the case study is assumed to be deterministic, while it is a dynamic environment in reality. The decomposition approach to the CII regulation requires a fixed limit for ship speed, while the actual CII value is calculated annually and periods of increased ship speed and emissions could be acceptable. Our investigation is limited to one specific vessel in one voyage planning scenario to illustrate the implications of the CII regulation. Validation for route planning is not in the scope of this research.

The organization of this article is as follows. The second section describes the carbon intensity indicator regulation. The third section illustrates how the models work, including the sea ice, ship performance, and routing models. Subsequently, the case study is demonstrated in the fourth section. The following section discusses the findings. The final section describes how the model can support shipping operations and proposes future work.

2. Carbon Intensity Indicator regulation

2.1. Definition of Carbon Intensity Indicator

The CII regulation was adopted by the IMO for the shipping industry and entered into force in 2023. The regulation comprises guidelines on how to determine the attained CII value and how to assess it. The carbon intensity indicator refers to the ratio of the mass of carbon dioxide in grams over the transport work in tonne-nautical miles in a calendar year. Eq. 1 shows how to calculate CII in general. The mass of carbon dioxide (M) is the product of the consumption of each type of fuel with a conversion factor associated with this fuel. The transit work (W) is calculated by the multiplication of the vessel's capacity (C) with the distance travelled (D). Capacity C is either deadweight or gross tonnage, depending on the vessel type, as defined in the regulation [9].

$$attained\ CII = \frac{M}{W} \tag{1}$$

2.2. Carbon intensity indicator for ice-classed vessels

The current study concentrates on the CII regulation for ice-classed vessels operating in ice-covered waters. The calculation of the attained CII is complicated in practice. IMO [14] introduced two correction factors to adjust transport work for ice-classed vessels: capacity correction factors and special ones for ice class 1A and 1A Super. According to the proposal for Marine Environment Protection Committee (MEPC) 76/3/5 [15], the justification for these factors is that the ice-classed vessels have smaller deadweight tonnage than equivalent vessels designed for operating in open water. The ice-classed vessels with 1A and 1A Super also have some limitations in installing fuel enhancement devices.

The CII regulation contains specific treatment for periods when a ship is sailing in ice conditions. In this case, the fuel consumption and the transport work are deducted from the CII calculation. IMO defines sailing in ice conditions as the sailing of an ice-classed vessel in a sea area within the ice edge [14]. MEPC 76/3/5 recognizes that ice-classed vessels consume more fuel when in ice conditions than when sailing in open waters in the same area [15]. In other words, given the same engine power, ice resistance forces the vessels to reduce operational speeds.

The generalized formula of CII with correction factors and exemptions is presented in Appendix A. The current study uses an example of a bulk carrier with ice class 1A Super. The corresponding CII formula for this scenario is presented in Eq. 2.

$$CII = \frac{\sum_j CF_j \times (FC_j - FC_{voyage,j})}{f_i \times f_m \times Capacity \times (D_t - D_x)} \tag{2}$$

where:

j represents the fuel type,

CF_j is the conversion factor of fuel type j from fuel mass to CO_2 mass,

FC_j is the total mass (in grams) of the consumption of fuel type j,

$FC_{voyage,j}$ is the mass (in grams) of fuel type j, which is deducted as an exemption when the vessel navigates in endangered conditions or in ice.

f_i represents the correction factor for the capacity of ice-class vessels,

f_m is the factor of ships having ice class 1A or 1A Super,

D_t is the distance (in nautical miles) travelled by vessels,

D_x is the distance (in nautical miles) travelled in exempt scenarios associated with $FC_{voyage,j}$.

2.3. Assessment of CII

The evaluation of attained CII values is as follows. A vessel is considered to meet the CII regulation if its annual attained CII value is less than a threshold called required CII. This threshold varies according to the year of the operation. IMO standardizes the required CII of the year 2019 as a reference point CII_{ref}. The required CII of the following years is decreased by Z% in comparison with the reference in 2019 [16]. The reference point for defined groups of ships is formulated in Eq. 3 [17]. Table 1 specifies the values of Z from 2020 to 2026.

$$CII_{ref} = a \times C^{-c} \tag{3}$$

where:

C is the capacity of the vessel,

a and c are parameters fitted through a regression model from initial data in the year 2019. Values of a and c are published in the regulation and provided in Appendix B.

For example, a bulk carrier with 76,180 tonnes Deadweight (DWT) has $a = 4745$ and $c = 0.622$. Hence, the required CII of the referenced year, namely 2019, is $CII_{ref} = 4.36$. The required CII for 2023 is 5% less than CII_{ref}, or $CII_{required,2023} = 4.14$.

The assessment of annual attained CII values follows the operational energy efficiency performance rating framework [18]. The CII performance of a vessel is assessed against statistically determined rating boundaries for the required CII value, including inferior, upper, lower, and superior boundaries [18]. There are five categories: A, B, C, D, and E, where the alphabetical order shows the ranking from the best to the worst performance. The expectation is that vessels have to achieve a rating of C or above. To simplify the evaluation, the current study uses the required CII as a limit to evaluate whether attained CII is acceptable or not. The required CII is equivalent to the mid-range of rating C in the assessment scheme, i.e., between the upper and lower rating boundaries.

Table 1
The values of reduction factor Z from 2020 to 2026 [16].

Year	Z%
2020	1%
2021	2%
2022	3%
2023	5%
2024	7%
2025	9%
2026	11%

2.4. CII calculation decomposition

The calculation of CII is done annually at the end of the calendar year. The concern is how to strategically operate a vessel to achieve the CII target set at the beginning of the year. This section proposes an approach to transform the annual requirement into a constraint for shipping transit interval of 1 km. Consider a single voyage of a vessel. This voyage has some transport work (W) and releases an amount of CO_2 while operating (M), thereby generating an instantaneous CII value. If every instantaneous CII value of a vessel in all individual voyages in a calendar year satisfies the required CII, then the annual attained CII of this vessel also meets the required CII. The following proves this statement.

Claim 1. If all individual voyages of a vessel meet the required CII, then the annual attained CII meets the required CII.

Proof.

First, we consider the two lemmas below

Lemma 1: $\forall a, b, x, y > 0, \frac{a}{x} = \frac{b}{y} \rightarrow \frac{a}{x} = \frac{b}{y} = \frac{a+b}{x+y}$

Lemma 2: $\forall a, b, x, y > 0, \frac{a}{x} \le \frac{b}{y} \rightarrow \frac{a}{x} \le \frac{a+b}{x+y} \le \frac{b}{y}$

Proofs of Lemma 1:

$$\frac{a}{x} = \frac{b}{y} \Longrightarrow ay = bx \Longrightarrow ax + ay = ax + bx \Longrightarrow a(x+y) = x(a+b) \Longrightarrow \frac{a}{x} = \frac{a+b}{x+y}$$

$$\frac{a}{x} = \frac{b}{y} \Longrightarrow ay = bx \Longrightarrow by + ay = by + bx \Longrightarrow y(a+b) = b(x+y) \Longrightarrow \frac{b}{y} = \frac{a+b}{x+y}$$

Proof of Lemma 2:

$$\frac{a}{x} \le \frac{b}{y} \Longrightarrow ay \le bx \Longrightarrow ax + ay \le ax + bx \Longrightarrow a(x+y) \le x(a+b) \Longrightarrow \frac{a}{x} \le \frac{a+b}{x+y}$$

$$\frac{a}{x} \le \frac{b}{y} \Longrightarrow ay \le bx \Longrightarrow by + ay \le by + bx \Longrightarrow y(a+b) \le b(x+y) \Longrightarrow \frac{a+b}{x+y} \le \frac{b}{y}$$

Next, we prove the claim.

Let CII_i, M_i, W_i represent the instantaneous attained CII, the mass of CO_2 emission, and transit work of the i^{th} voyage, respectively, with $1 \le i \le k$.

Let α be the required CII. Assume the vessel has k voyages in a calendar year.

The CII calculations for all voyages are:

$$CII_1 = \frac{M_1}{W_1}$$

$$CII_2 = \frac{M_2}{W_2}$$

…

$$CII_k = \frac{M_k}{W_k}$$

The annual CII is determined by the following:

$$CII_{annual} = \frac{M_1 + M_2 + \ldots + M_k}{W_1 + W_2 + \ldots + W_k}$$

If $CII_1, CII_2, \ldots, CII_k \leq \alpha$ and $CII_1 = CII_2 = \ldots = CII_k$, then $CII_{annual} \leq \alpha$, according to Lemma 1.

Else:

Assume: $\min_{1 \leq i \leq k} CII_i = \beta_1 \leq \alpha$, $\max_{1 \leq i \leq k} CII_i = \beta_2 \leq \alpha$, then $\beta_1 \leq CII_{annual} \leq \beta_2 \leq \alpha$, according to Lemma 2. End of proof.

As a result, Claim 1 can refer to a similar conclusion for arbitrarily smaller portions of the total annual work. Given a DWT of a vessel, if every transit of the vessel in a unit distance (e.g. 1 km or 1 NM) meets the required CII, the CII value of the entire voyage also meets the requirement of CII. Therefore, the annual attained CII will be within the target.

In summary, this section describes the carbon intensity indicator, how to determine the required CII for each type of vessel, the exemption rule for voyages in ice, and the decomposition approach we use to maintain the annual CII value by controlling instantaneous CII values. In the next section, more analysis of the instantaneous CII is discussed with a specific vessel as a case study to identify the appropriate action for operations.

3. Modelling

This research studies a voyage of a hypothetical bulk carrier operating in the Canadian Arctic in July. The vessel has 76,180 DWT with ice class 1A Super. The required CII of this bulk carrier in 2023 is 4.14, as mentioned in Section 2. This section introduces a ship performance model for this vessel, how sea ice in the ice chart is modelled, the application of the CII regulation, and the route optimization model. The ship's particulars and environmental parameters are presented in Table 2. Note that an ice flexural strength of 150 kPa represents that of decaying first-year sea ice (i.e., warm summer ice) and is based on estimates for the Canadian Arctic in July [19,20].

3.1. Ship performance model

This section describes the ship performance model for the bulk carrier considered in the case study. The ship performance model estimates resistance, powering, and fuel consumption in ice and open water. Fig. 1 outlines the elements of the ship performance model.

Ice resistance can be estimated using any one of the many methods that have been proposed over the years (e.g. [21–23]). Most of the current approaches estimate level ice resistance, or "equivalent" level ice resistance. In reality, ice conditions are more complex with various sizes, forms, and stages of development. Some recent work proposes ice resistance formulations for ice floes [24–26]. In our case, ice resistance is estimated using model scale ice resistance test results in level ice for a similar vessel type and size and scaled to match the case study vessel to simplify the problem.

The model test and analysis procedure follow the standard procedure of the International Towing Tank Conference (ITTC) [27]. The ice resistance is assumed to comprise three main components: ice buoyancy resistance (R_B), ice clearing resistance (R_{CL}), and ice breaking resistance (R_{BR}). The three components are summed to obtain total ice resistance (R_{ice}), as presented in Eq. 5. The modelled vessel is tested in level ice and pre-sawn ice conditions to determine each component of the ice resistance. Regression analysis of the model test results provides the coefficients of equations to estimate ice resistance at both model and full scale at various ship speeds. Eqs. 6–8 present the equations for each ice resistance component.

The ice resistance components are dependent on the ship beam (B), ice thickness (h_i), and environmental parameters defined in Table 2. In Eq. 6, the ice buoyancy resistance is speed-independent but dependent on ship draft (T), while the ice clearing and ice breaking resistance vary according to ship speed (V) in Eqs. 7 and 8. Ice clearing and ice breaking resistance are also dependent on non-dimensional ice thickness Froude (F_N) and ice strength (S_N) numbers, respectively. The ice thickness Froude and ice strength numbers are calculated using Eqs. 9 and 10, respectively. Non-dimensional coefficients and exponent terms for the components of ice resistance are obtained through regression analysis of the test results and are presented in Table 3.

$$R_{ice} = R_B + R_{CL} + R_{BR} \tag{5}$$

$$R_B = C_B \times (\rho_w - \rho_i) \times g \times B \times T \times h_i \tag{6}$$

$$R_{CL} = C_{CL} \times {F_N}^{\exp CL} \times \rho_i \times B \times h_i \times V^2 \tag{7}$$

$$R_{BR} = C_{BR} \times {S_N}^{\exp BR} \times \rho_i \times B \times h_i \times V^2 \tag{8}$$

$$F_N = V \Big/ \sqrt{g h_i} \tag{9}$$

$$S_N = V \Bigg/ \sqrt{\frac{(\sigma_f \times h_i)}{(\rho_i \times B)}} \tag{10}$$

The ice resistance model tests do not provide an estimate for open water resistance (R_{OW}). The current study adopts the empirical Holtrop method to estimate open water [28,29]. The equation for open water resistance (R_{OW}) for the case study vessel is provided by Eq. 11. Total resistance (R_T) is the sum of ice resistance (R_{ice}) and open water resistance (R_{OW}).

$$R_{OW} = 24.5V^2 - 50.7V + 40.9 \tag{11}$$

The effective power (P_E) necessary to propel the vessel through ice and open water is estimated as the product of total resistance (R_T) and ship speed (V), as per Eq. 12. Estimating the required power (P_R) to achieve a given effective power (P_E) requires consideration of propulsive efficiencies, as presented in Eq. 13. The propulsive efficiencies considered in the ship performance model are defined in Table 4. Note that a constant open water efficiency is modelled for the current study. While the installed engine power is 14.28 MW, the recommended engine power is derated by 15% to 12.14 MW in the current study.

$$P_E = R_T \times V \tag{12}$$

$$P_R = P_E / \eta_H \times \eta_O \times \eta_R \times \eta_S \tag{13}$$

Estimating fuel consumption requires consideration of the specific fuel oil consumption rate (SFOC) of the engine. The SFOC for the engine is modelled as a function of engine load and presented in Fig. 2. For a given distance (d) and ship speed (V) travelled in an ice regime, the mass of consumed fuel is estimated using Eq. 14.

$$Fuel\ consumption = (d/V) \times P_R \times SFOC \tag{14}$$

3.2. Modelling sea ice data

Resistance in ice is a function of speed and ice properties, including thickness, flexural strength, and density. Estimates for ice flexural strength and density are held constant, as presented in Table 2. Ice thickness is modelled using sea ice data obtained from published ice charts from the Canadian Ice Service (CIS). Sea ice data are reported

Table 2
Vessel and environmental parameters relevant to the ship performance model.

Ship parameters		Environmental parameters	
Length, L	220 m	Sea ice density, ρ_i	890 kg/m^3
Beam, B	32.26 m	Sea water density, ρ_w	1025 kg/m^3
Draft, T	14.40 m	Ice flexural strength, σ_f	150 kPa
Block coefficient, C_b	0.86	Gravitational acceleration, g	9.81 N/kg
Form factor, k	0.37		
Installed engine power	14.28 MW		

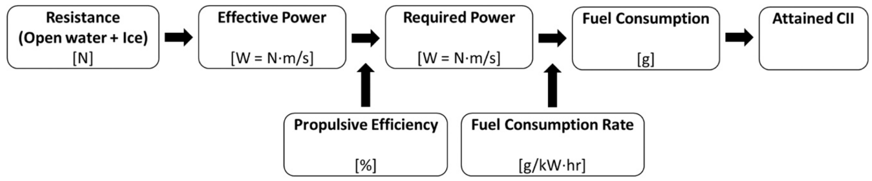

Fig. 1. Elements of the ship performance model.

Table 3
Non-dimensional coefficients and exponents for ice resistance equations.

Variable	Description	Value
C_B	Coefficient of buoyancy resistance	1.26
C_{CL}	Coefficient of clearing resistance	2.50
C_{BR}	Coefficient of breaking resistance	2.37
expCL	Exponent term for clearing resistance	-0.98
expBR	Exponent term for breaking resistance	-1.90

Table 4
Modelled propulsive efficiencies.

Efficiencies & allowances	Symbol	Value
Hull efficiency	η_H	1.10
Open water efficiency	η_O	0.60
Relative rotative efficiency	η_R	1.00
Shaft efficiency	η_S	0.94

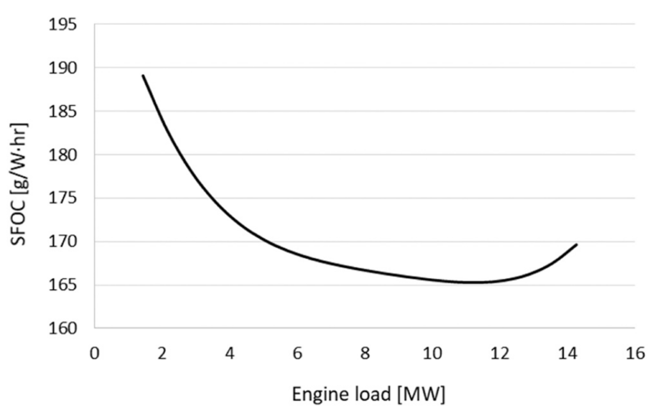

Fig. 2. Specific fuel oil consumption rate as a function of engine power.

using egg codes, following World Meteorological Organization (WMO) guidelines [30]. For an area in which the ice conditions are represented by an egg code, the ice cover is described in terms of partial concentrations, stages of development (corresponding to an ice thickness range), and floe sizes for each ice type within the area. These areas are typically referred to as ice regimes.

For the purpose of the ship performance model, it is necessary to modify the ice chart data to estimate the resistance of the ship in ice. An approach developed by Frederking [31] is adopted. For a given distance in an ice regime, the ice regime is modelled as consecutive sections of each ice type and open water. The partial distances for each ice type and open water are calculated as the product of the associated partial concentrations and the total distance travelled in the ice regime. Each ice type is modelled as uniform level ice thickness. WMO stages of development, thickness ranges, and associated ice thickness values modelled for the current study are presented in Table 5.

The maximum attainable speed in ice is dependent on ice characteristics and limited by available engine power. To illustrate the method of calculating average attainable speed in an ice regime, consider a ship transiting 10 km through an ice regime composed of partial

Table 5
WMO ice types, thickness ranges, and ice thicknesses modelled for the current study.

Stage of development	Thickness range (cm)	Modelled ice thickness (m)
New	< 10	0.1
Nilas	< 10	0.1
Young	10 – 30	0.3
Grey	10 – 15	0.15
Grey-white	15 – 30	0.3
First year	≥ 30	0.75
Thin first year	30 – 70	0.7
Thin first year, first stage	30 – 50	0.5
Thin first year, second stage	50 – 70	0.7
Medium first year	70 – 120	1.2
Thick first year	> 120	2
Old	-	3
Second year	-	2.5
Multi-year	-	3

concentrations of 1/10th grey ice, 2/10th thin first-year ice, and 7/10th open water. The ice regime is modelled as partial distances of 15 cm thick ice for 1 km, 70 cm thick ice for 2 km, and open water for 7 km. Using the ship performance model with an available engine power of 12.14 MW, the attainable speeds are: 7.03 m/s (13.7 knots) in 15 cm thick ice, 5.00 m/s (9.7 knots) in 70 cm thick ice, and 7.43 m/s (14.4 knots) in open water. The total time to transit the ice regime can be estimated based on partial distances and attainable speeds. An average attainable speed of 6.74 m/s is calculated based on the total time and total distance to transit the ice regime. Table 6 summarizes the calculation of the average attainable speed for the ice regime. Note that while the example shows the calculation of attainable speeds, the agent may adopt reduced speeds due to regulatory constraints or optimization based on the modelled cost function.

3.3. Modelling CII using V_{eco}

The current study aims to help operators adhere to the CII regulation through voyage planning. The CII value depends on the vessel's fuel consumption and transport work. Fuel consumption is a function of ship speed, given the ship's particulars and environmental parameters. If the distance travelled is 1 km, the transport work can be determined, which means the instantaneous CII depends only on the ship's speed.

Let us consider a special value of ship speed, which we call the

Table 6
Example calculation of average attainable speed for an ice regime.

Ice type/ open water	Thickness (m)	Partial concentration (tenths)	Partial distance (km)	Attainable speed (m/s)	Time (hr)
Grey	0.15	1	1	7.03	0.040
Thin first-year	0.70	2	2	5.00	0.111
Open water	-	7	7	7.43	0.262
			Total time (hr)		0.412
			Average speed (m/s)		6.74

economic speed, or V_{eco}, at which the instantaneous CII value corresponds to the required CII. The next step is to determine a speed limit V_{eco} of the vessel over a distance interval of 1 km. Fig. 3 illustrates an example of fuel consumption in grams of the bulk carrier by speed and ice thickness. Each curve represents the fuel consumption of the vessel in different conditions, including open water and ice, with thicknesses from 0.2 to 0.8 m. Fig. 4 is the attained CII estimates of this vessel over a 1 km interval. As can be seen in Fig. 4, the CII curves increase monotonically in the speed range from 4 knots and above. The horizontal dashed line is the required 2023 CII for this vessel of 4.14. The V_{eco} of the vessel in open water is about 12.9 knots. Similarly, the speed limits of ice transit can also be determined using Fig. 4. However, the V_{eco} in ice is not applicable because periods when sailing in ice conditions are exempt from the calculation of attained CII, as per the regulation.

Therefore, if the bulk carrier is operated at a speed below or equal to the V_{eco}, compliance with the CII regulation will be assured.

3.4. Route optimization model

The intent of this study is to find a route for vessels from point A to point B in the presence of ice-covered waters. The goal is to optimize multiple objectives, including distance travelled, voyage time, and fuel consumption. The constraints are that the operations must adhere to POLARIS and CII regulations. The solution is a proposed route, in which the three operational objectives are optimized. The optimal route includes waypoints and directions from A to B with the suggested speeds along the path.

POLARIS promotes structural safety for vessels operating through ice-covered waters [32]. A Risk Index Outcome (RIO) is calculated based on the ice capability of the vessels and an ice regime. Eq. 15 shows the formula for RIO. If RIO < 0, operators cannot plan a voyage through this ice regime.

$$RIO = \sum_i RIV_i \times C_i \tag{15}$$

where RIV_i is the predetermined Risk Index Value of the i^{th} ice type, and C_i is the corresponding partial concentration of the ice type or open water [32].

The current study uses a Canadian Ice Service ice chart as the map. The ice chart is discretized into a grid world, where each cell represents a geographical type, such as land, open water, or an ice regime. Navigation through the grid is modelled by a graph. Each cell of the grid is a vertex, and its connections to the eight closest neighbours are edges of the graph. The edge is associated with a weight W, representing a cost to traverse from one node to another at a certain speed. In the model, vessels can move in eight directions: north, northeast, east, southeast, south, southwest, west, and northwest. The speed varies from 0 to the maximum capable speed of the vessel in increments of 0.5 knots.

The model applies Dijkstra's algorithm [33] to search for the best route. It starts at point A and greedily searches for the next vertex to traverse by choosing the option with the least cost among all possibilities. The algorithm ends when the destination point B is reached. The cost function is aggregated from the three operational factors, including distance travelled, voyage time, and fuel consumption. Eq. 16 shows how the cost is calculated. Regarding adherence to constraints, the model adheres to POLARIS by avoiding grid cells containing ice regimes that correspond to RIO values below zero, and adheres to the CII regulation through speed selection, such that speed is equal to or less than V_{eco}. If the traversal violates constraints, i.e., the vessel goes to a prohibited ice regime (RIO < 0) or the speed is higher than the V_{eco}, the cost is penalized at $+\infty$.

$$cost = k \times distance + m \times time + l \times fuel\ consumption \tag{16}$$

where k, m, and l are coefficients.

The model uses weighted summation to solve multiple objective optimization problems. There is no definitive way to define an optimal route in a multi-criteria scenario. Some operations consider voyage time the most important factor, while others prefer fuel cost. Hence, the choice of weighting parameters k, m, and l depends on the judgement of the system designer. The ratio of k:m:l is relative. If time is more important for the operation, the values of k, m, and l are set so that $m \times time$ is higher than $k \times distance$ and $l \times fuel\ consumption$. Similarly, their weights can be tuned to reflect the relative importance of each factor. In this research, the parameters are set as follows: $k = 1$, $m = 10^7$, $l = 1$. These values prioritize reducing voyage time. Achieving a short voyage time means the vessel has to increase its speed, consume more fuel, and emit more carbon dioxide.

4. Case studies

This section performs voyage planning for the aforementioned bulk carrier with ice class 1A Super, from Arctic Bay, Nunavut, towards Europe through Baffin Bay. The operation is supposed to be in the summer of 2023 and adheres to the POLARIS and CII regulations. The vessel is assumed to operate independently without support from icebreakers. The required CII of this bulk carrier in 2023 is 4.14.

The ice conditions are assumed to be similar to the Canadian Ice Service ice chart on July 26, 2021, shown in Fig. 5 [34]. Another assumption is that the ice conditions do not change during this period of time. As can be seen on the map, point A is a port in Arctic Bay, and point B is a waypoint that the vessel needs to go through on the way to Europe.

CII guidelines are modified to demonstrate the implications of this regulation on route decisions. There are four cases presented, including for operations that do not adhere to CII (Case 1), and operations that adhere to CII with and without exclusion for sailing in ice conditions. Note that the POLARIS regulation is adhered to in all cases, while the CII regulation is an additional constraint for Cases 2, 3 and 4. The RIO values for the bulker for each ice regime in the case study are shown in Table 7, according to the POLARIS guidelines. The navigable regimes include Y, Z, BB, CC, FF, and GG.

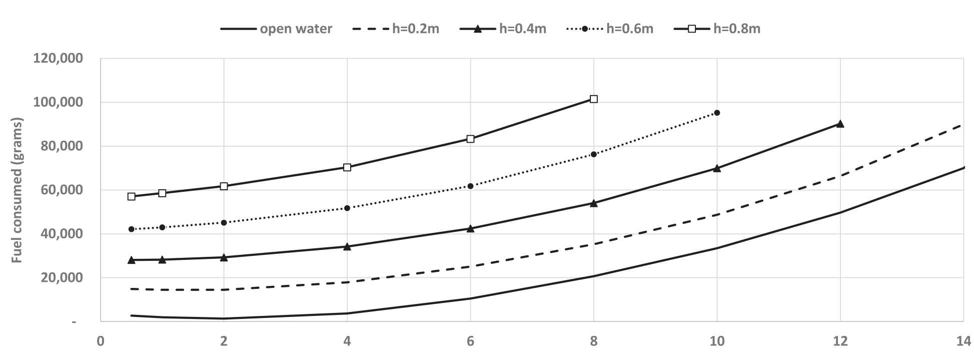

Fig. 3. Fuel consumption of a bulk carrier in 1 km by speed and ice thickness.

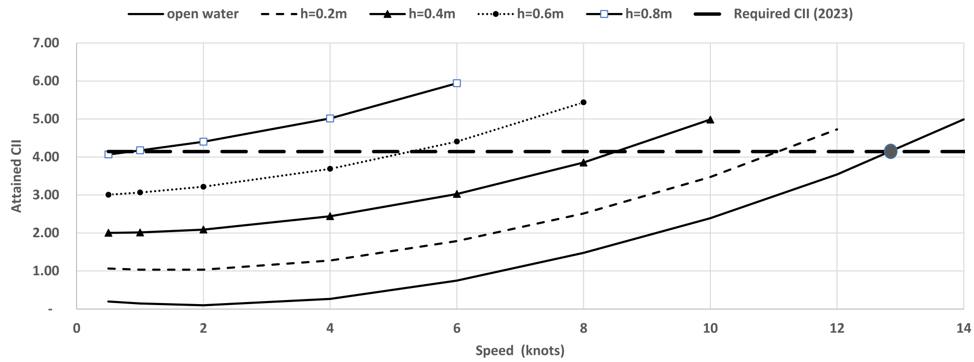

Fig. 4. CII calculation of a bulk carrier in 1 km by speed and ice thickness.

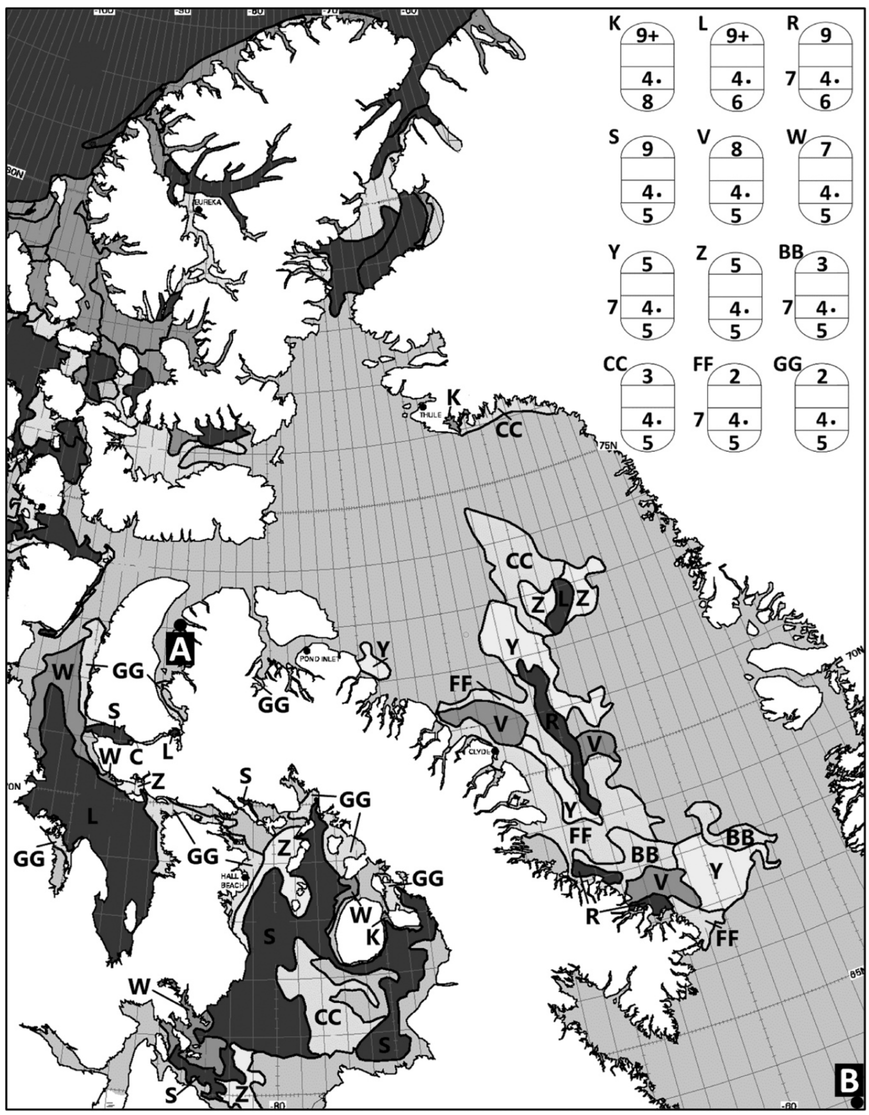

Fig. 5. Ice chart of the Canadian Eastern Arctic on July 26, 2021.
Used with permission. © His Majesty the King in Right of Canada, as represented by the Minister of the Environment Canada, [2022].

Table 7
Risk Index Outcome of the vessel in the regimes in the ice chart.

Regime	K	L	R	S	V	W	Y	Z	BB	CC	FF	GG
RIO	-20	-20	-15	-15	-10	-5	5	5	15	15	20	20

4.1. Case 1: Not adhering to CII

Case 1 represents a scenario in which the vessel does not adhere to the CII regulation. The vessel only adheres to the POLARIS guidelines. This scenario defines a baseline for comparisons.

Fig. 6 shows the proposed route for the vessel from point A to point B. As can be seen, the vessel is suggested to move east from A to waypoint 5 and then turn southeast and south to arrive at B. Most of the legs of the voyage are in open water, where the speed is 14.0 knots. The vessel sails in ice regime CC (waypoints 5–6) and regime BB (near waypoint 8) at 8 knots. Although the CII regulation is not adhered to in this case, the attained CII of the voyage can still be estimated based on estimates of fuel consumption and distance travelled. The attained CII for the voyage is reported at 5.22.

Note that regimes BB and CC have two elements: the thick first-year ice (3/10th) and open water (7/10th). As exemplified in Section 3.2, the average speed of 8 knots results from the aggregation of speeds of 4 knots in the thick first-year ice and 14 knots travelling in the open water. The vessel cannot operate at more than 4 knots in this thick ice because of the limitation of the engine power of 12.14 MW. In open water parts of the ice regimes, the vessel speeds up to 14 knots. The algorithm chooses speeds in increments of 0.5 knots.

4.2. Case 2 Adhering to CII, both in open water (OW) and ice-covered water.

Case 2 represents a scenario in which the vessel adheres to the CII regulation, but without adjustment for sailing in ice conditions. No voyage adjustment means the calculation of CII does not exclude periods when the vessel is transiting through ice.

The optimal route for the vessel in Case 2 is displayed in Fig. 7. The vessel transits in open water areas for the entire voyage, moving northeast from A to waypoint 4, then going east to waypoint 5 and sailing south and southeast to B. However, the speed of the vessel is reduced to 12.5 knots. The reduction in speed of the vessel from 14 knots to 12.5 knots is because the operation has to comply with the CII regulation. The speed of the vessel in the open water cannot be higher than V_{eco} of 12.9 knots, as introduced in Section 3.3. The attained CII is 3.88, which meets the requirement of the CII regulation.

4.3. Case 3 Adhering to CII in OW only.

Case 3 represents a scenario in which the vessel adheres to the CII regulation, including the exemption for sailing in ice conditions. The calculation of CII excludes the portions of the voyage spent sailing in sea ice from the formula [14]. This case represents the actual requirement of the current CII regulation.

Fig. 8 illustrates the optimal route in Case 3. The route is similar to that of Case 1 but with a different speed profile in open water regimes. The vessel travels in open water to the east through waypoints 1–5, then goes southeast in the ice regime CC to waypoint 6. It continues in open water until it reaches the ice regime BB just before waypoint 8. The average speeds of the vessel in open water, and ice regimes BB and CC, are 12.5 knots, 8 knots, and 8 knots, respectively. After that, it keeps sailing to the destination in open water at 12.5 knots.

In regimes BB and CC, the vessel operates at 4 knots and 14 knots in the thick first-year ice portion and the open water portion, respectively. In the open water portion of the ice regimes, the vessel is able to speed up to 14 knots without being limited by the V_{eco} due to the exemption rule of the CII regulation.

The fuel consumed over a 1 km interval at 4 knots in the thick first-year ice is 248,664 g, according to the ship performance model. The associated instantaneous CII is 17.73, which is significantly higher than the required CII of 4.14. This fuel consumption is nearly five times higher than the amount of 54,371 g of fuel needed for 1 km at 12.5 knots in open water. However, the CII regulation only applies to the voyage in open water, so the attained CII of the vessel is recorded as 3.88.

4.4. Case 4 Adhering to CII in OW only, with strategic consideration of the ice edge.

The ice edge indicated on an ice chart has no exact boundary

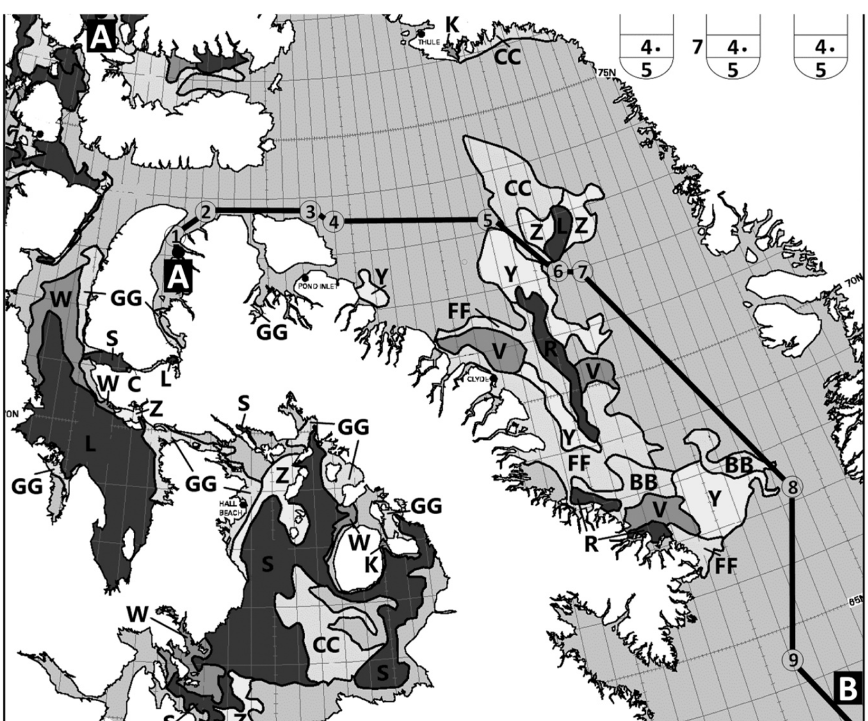

Fig. 6. Route suggestion for Case 1.

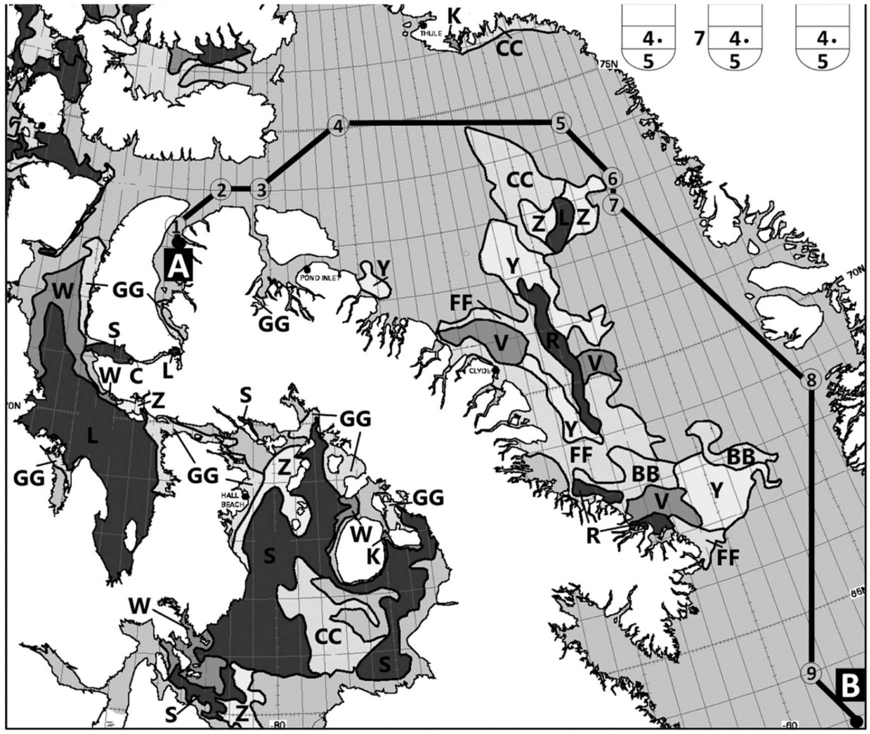

Fig. 7. Route suggestion for Case 2.

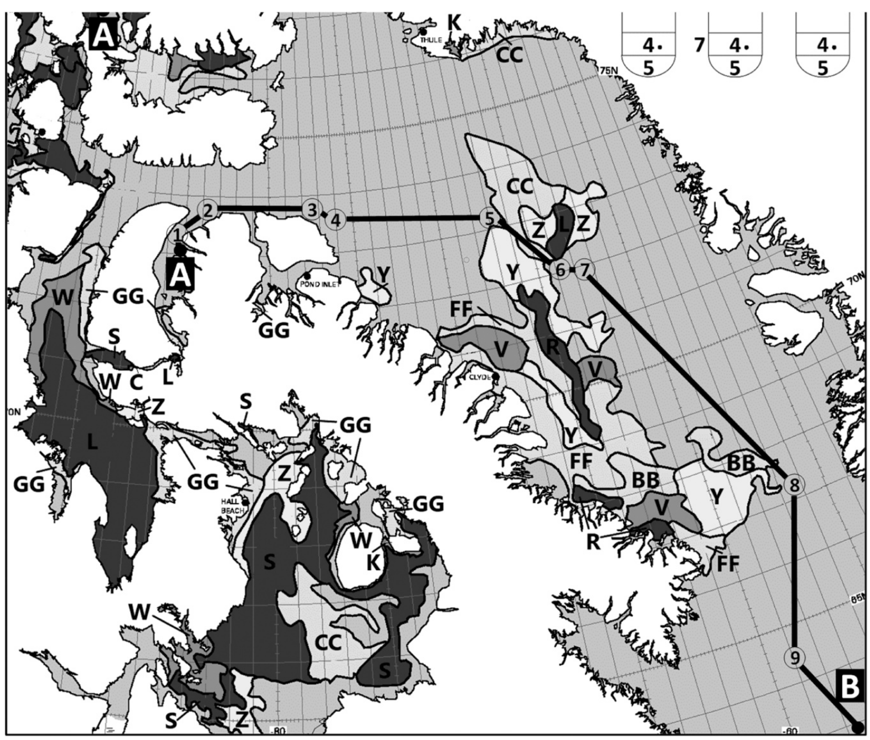

Fig. 8. Route suggestion for Case 3.

between ice floes and open water. The boundary line separating ice regimes and open water on the ice chart is approximately a few kilometres by the scale of the map. Case 4 introduces a scenario when the vessel moves along the open water areas next to the ice edge. In our model, any open water grid cell that is immediately adjacent to an ice regime is marked as a member of the ice edge set. If operators and regulators consider the vessel transiting in ice when sailing along the ice edge, it is excluded from the CII calculation.

The result of Case 4 is shown in Fig. 9. The resultant route has some changes compared to that of Case 3. The vessel intentionally sails more in the open water adjacent to ice regimes (waypoints 6–7, waypoints 8–10) with a speed of 14 knots. The remaining legs are the same as that of Case 3, with open water speeds of 12.5 knots. The attained CII is 3.88.

Table 8 summarizes the measurements of operational objectives,

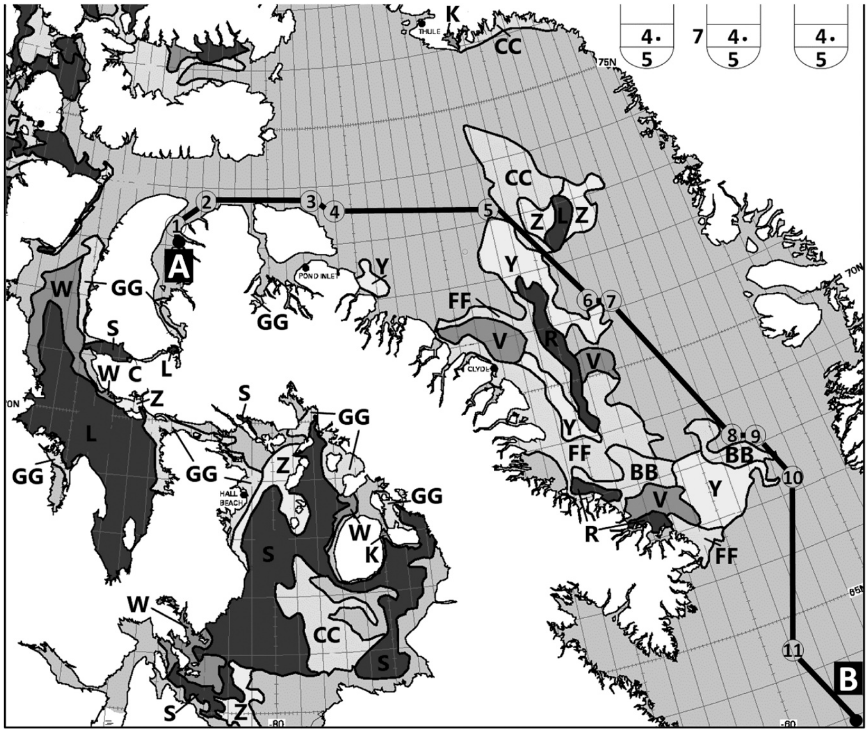

Fig. 9. Route suggestion for Case 4.

Table 8
Indicators of the optimal routes in all cases.

	distance (km)	time (h)	fuel consumption (grams)	attained CII
Case 1: Not adhering to CII	2018	41.9	147,880,431	5.22
Case 2: Adhering to CII, in OW + ice	2265	50.3	123,143,177	3.88
Case 3: Adhering to CII in OW only	2018	46.4	118,309,282	3.88
Case 4: Adhering to CII in OW only, with strategic consideration of the ice edge	2018	45.6	123,275,964	3.88

including total distance travelled, total voyage time, total fuel consumption, and the attained CII of the vessel in this voyage. Note that although Cases 3 and 4 have reported CII values of 3.88, actual CII values are higher based on total distance and fuel consumption. More findings are discussed in the next section.

5. Discussion

5.1. Impact of CII on operations

The CII regulation has an impact on the route selection of vessels in general. When the operations do not adhere to the CII regulation, the optimal speed of the vessel in open water is 14 knots, as illustrated in Case 1 and some segments of Case 3 and Case 4. With the application of the CII regulation, the chosen open water speed reduces to 12.5 knots to ensure the attained CII meets the requirement. The reduction in speed results in a reduction in the amount of carbon emitted to the environment. The attained CII decreases from 5.22 in Cases 1 to 3.88 in Case 2 to meet the required CII of 4.14. This result meets the expectation of the CII regulation. The maximum allowable speed of the vessel is about 12.9 knots, but the granularity of speed in our model is 0.5 knot, so it leaves a gap here.

The CII regulation also affects operations in ice-covered waters. The exemption rule for ice-class vessels sailing in ice conditions gives them an advantage [14]. The speed of the vessel is not constrained by the V_{eco} in ice regimes because the CII regulation is not applicable, and the operators only need to adhere to the POLARIS guidelines. Ship speeds in the regime can exceed the V_{eco} limit as long as the engine is capable, no matter how much more fuel is consumed to execute this action. The only factor influencing speed choice is the optimization function when the vessel selects the optimal speed. For example, the ice-classed bulk carrier is suggested to operate in open water in Case 2 because the vessel has no other choices. Transiting through the ice in this case would require a lot of fuel – considerably more than would be allowed according to the CII constraint. According to the ship performance model, achieving an instantaneous CII below 4.14 in thick first-year ice is not possible. Meanwhile, the route in Case 3 can sail through ice simply because of the exemption rule. Hence, this exemption benefits ice-strengthened vessels and can be exploited to enable "optimized" operations through ice-covered waters. In addition to POLARIS, the ship must still be operated prudently, so as to avoid risking structural damage due to ice. Even if RIO > 0, the energy of a collision with ice still increases with speed in reality. However, this problem is out of the scope of the current study.

The sailing in ice exemption rule gives vessels more possibilities in navigation without violating the CII regulation. As a consequence, the actual fuel consumption (and corresponding CII) of the vessel might be much higher than the required CII, although the reported CII value is within the permissible range. In Case 3 and Case 4, the reported CII value is 3.88, which is lower than the required CII of 4.14. If there is no exemption, the actual CII values of these two cases are 4.18 and 4.36, respectively.

Decarbonization for shipping operations is the ultimate goal of the CII regulation. From Table 8, the regulation forces the operations to reduce a significant amount of fuel consumption: from 148 tonnes with a CII of 5.22 in the base case (Case 1) to around 118–123 tonnes with a CII of 3.88 in the remaining three cases. Critics might argue the exemption for sailing in ice is bad for the environment because the actual carbon emission rate is higher than the reported value. This concern is valid in most cases. A counterexample for the critique of this rule is shown in Case 2 and Case 3. Without the exemption for sailing in ice, the route in Case 2 is longer, and the amount of fuel consumption is 123 tonnes, with an actual CII of 3.88. Meanwhile, the route in Case 3 only requires 118 tonnes of fuel despite generating a higher actual CII of 4.18. The operation in Case 3 is more efficient than that of Case 2, in terms of the amount of carbon emission. As illustrated by this example, the exemption for sailing in ice is not always bad for the environment.

Sailing along the ice edge might be an unanticipated phenomenon arising from the CII regulation. The current study explores this in Case 4, where the vessel sails in open water along the boundary of the ice regime. These legs can be reported as operations in ice, thereby making them eligible for the exemption. In Case 4, the vessel's speed peaks at 14 knots along the ice edge, while the current CII regulation (Case 3) only allows operating at 12.5 knots in open water. Although it poses a risk for the vessel to sail next to the ice, the vessel would rather sail along the ice edge to gain more favourable outcomes in terms of economic optimization.

The CII regulation does not always have an impact on a vessel's operation. If the design speed of the vessel is less than the V_{eco} referred by CII guidelines, CII compliance has no impact on current operations.

5.2. Sensitivity assessment

There are several control parameters in our model, such as the value of decayed ice flexural strength, the ice class of the vessel, and the calibration of objectives in the optimization model. Different values of parameters affect the results of the optimal route. A comprehensive sensitivity analysis is not the focus of the current study. However, in this section some scenarios are selected to evaluate the sensitivity of the model. Note that Case 3 becomes the baseline for the assessment because it reflects the practical application of the current CII regulation. Each test contains only one change compared to the setting of Case 3.

The first assessment considers ice flexural strength. The ice flexural strength used in our baseline case (150 kPa) is relatively lower than the normal range in the literature because we assume the sea ice encountered during a summertime voyage is decayed, and therefore weak. If we used an ice flexural strength value of 500 kPa, the total resistance of the thick first year ice rises 70–80% with the ship's speed in the range of 2–4 knots. The resultant route has a slight change. The vessel's speed in thick first year ice decreases from 4 knots to 2.5 knots, leading to an average speed of 5.9 knots in the ice regime CC. The segment from waypoint 7 to waypoint 8 also shifts east to the open water to avoid the ice regime BB. The attained CII remains unchanged. The impact of the ice flexural strength parameter on routing is not significant in this case because the period of ice transit is less than 6% of the entire voyage.

The ice class of the vessel is another factor in the operations. The current ice class of the vessel is 1A Super. If its class is changed to 1C or to PC6, the route is unchanged. The ice regimes BB and CC are navigable for any ice-classed vessel, according to POLARIS. The higher ice class has more possibilities for route selection but the current suggested route optimizes the operations.

The selection of parameters k, l and m of the cost function also impacts route planning. The current setting prioritizes the time factor to encourage the vessel to operate at high speeds. If the relative ratio between them changes, the result changes accordingly. For example, when the fuel consumption factor increases 10 times, or $k{:}m{:}l = 1{:}10^7{:}10$, the resultant route is similar to Case 3, but the speeds along the route vary. The speed in open water reduces from 12.5 knots to 9 knots, while the speeds in ice regimes BB and CC also reduce from 8 knots to 6.6 knots. The reason is that the model determines 9 knots is the optimal speed for the vessel. The attained CII is only 2.2. If the factor of the fuel consumption increases 100 times, or $k{:}m{:}l = 1{:}10^7{:}100$, the result changes significantly, where the route is entirely in open water, as in Case 2, with speeds at 4.5 knots. The CII value in this scenario reduces to 0.36.

Last but not least, the change of the required CII by year should be considered. The required CII of the vessel in the year 2023 is 4.14. The requirements for three following years (2024, 2025, and 2026) are 4.06, 3.97, and 3.88, respectively. The current result shows the suggested route still meets the requirements of CII regulation, where all of the suggested routes achieve the CII at 3.88. Assume that a required CII of a year in the future is 3.40, approximately a 22% reduction of the reference year. This would require a slight change of the route where the direction is the same as that of Case 3, but the speeds in open water reduce from 12.5 knots to 11.5 knots.

6. Conclusion

This research investigates the implications of the CII regulation for vessels in ice-covered waters. The analysis is done through a case study of a bulk carrier with ice class 1A Super. An approach is applied to convert the annual requirement of the CII regulation to ship speed limits based on the instantaneous CII values of vessel. The study considers several scenarios to compare operations with and without adherence to the CII regulation for vessels transiting in ice. The result shows that the CII regulation has an impact on shipping operations. The vessel must slow the operational speed to a certain level to achieve the required CII. Moreover, it is anticipated that ice-classed vessels might sail more in ice and near the ice edge to lower the reported CII value while maintaining optimal operations.

The current study provides a means to support shipping operations to operate safely within the POLARIS guidelines and in adherence to the CII regulation. The framework in this study could be used as a voyage planning tool for operators to find the best strategy for operations without violating rules. The framework can also serve as a tool for policy-makers to examine changes to the CII regulation, such as modifications of reference lines, required CII values, correction factors, and evolution of exemption rules. The implication analysis helps predict the impacts and consequences for the environment and the shipping industry.

The current study has some limitations. Firstly, the ice environment is assumed to be deterministic according to an ice chart. However, sea ice is dynamic, drifting and deforming over time. More work should be done to address the ice dynamics so that the route suggested is more accurate in terms of optimization and compliance with the CII regulation. The route should also be smoothened to reflect reality. Secondly, the determination of V_{eco} is a mechanism to control the CII. As discussed, V_{eco} is a fixed limit for the entire calendar year. This value should be updated according to the current data of the vessel. An adaptive V_{eco} limit is needed to make shipping operations more flexible. Thirdly, the current research investigates only one type of vessel in one geographic area. Future research might have a full-scale evaluation of the CII regulation. More geographical scenarios with different types of vessels should be tested to help the decision-makers have comprehensive viewpoints on the impacts of the new regulations on the current operations. Fourthly, the ship performance model used in the current study is appropriate for the chosen vessel in level ice. Investigating alternate ship performance models that suit multiple types of vessels in different conditions of sea ice is an area for future work. Finally, the study generates route planning using a route optimization tool, where many parameters are chosen by the system's designer. The routes are not validated by experts. Future work should perform route validation to improve credibility.

CRediT authorship contribution statement

T.T. Tran: Data curation, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing. **T. Browne:** Data curation, Formal analysis, Investigation, Supervision, Writing – original draft, Writing – review & editing. **B. Veitch:** Conceptualization, Formal analysis, Funding acquisition, Project administration, Supervision, Writing – review & editing. **M. Musharraf:** Supervision, Writing – review & editing. **D. Peters**: Supervision, Writing – review & editing.

Declaration of Competing Interest

None.

Data Availability

No data was used for the research described in the article.

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Appendix A

The generalized formula of CII calculation is presented in Equation A.1 [14].

$$CII = \frac{\sum_j CF_j \times \left\{FC_j - \left(FC_{voyage,j} + TF_j + (0.75 - 0.03y_i) \times \left(FC_{electrical,j} + FC_{boiler,j} + FC_{other,j}\right)\right)\right\}}{f_i \times f_m \times f_c \times f_{iVSE} \times Capacity \times (D_t - D_x)} \tag{A1}$$

where:

j represents the fuel type,

CF_j is the conversion factor of fuel type j from fuel mass to CO_2 mass,

FC_j is the total mass (in grams) of the consumption of fuel type j,

$FC_{voyage,j}$ is the mass (in grams) of fuel type j, which is deducted as an exemption when the vessel navigates in endangered conditions or in ice.

TF_j is the amount of fuel type j consumed for the purpose of ship-to-ship or shuttle tanker operation,

y_i is a consecutive numbering system, $y_{2023} = 0, y_{2024} = 1, y_{2025} = 2, \ldots$.

$FC_{electrical,j}, FC_{boiler,j}, FC_{other,j}$ represent the consumption of fuel type j in the operations that might be deducted for electrical, boiler, or other purposes. Detail of these factors in referred to (reference).

f_i represents the correction factor for the capacity of ice-class vessels,

f_m is the factor of ships having ice class 1 A or 1 A Super,

f_c is the chemical tankers' capacity correction factor,

f_{iVSE} is the correction factor for voluntary structural enhancement,

D_t is the distance (in nautical miles) travelled by the vessels,

D_x is the distance (in nautical miles) travelled in exempt scenarios associated with $FC_{voyage,j}$.

Appendix B

Parameters for determining the 2019 ship type specific reference line [17].

Ship type		Capacity	a	c
Bulk carrier	279,000 DWT and above	279,000	4745	0.622
	less than 279,000 DWT	DWT	4745	0.622
Gas carrier	65,000 and above	DWT	14405E7	2.071
	less than 65,000 DWT	DWT	8104	0.639
Tanker		DWT	5247	0.610
Container ship		DWT	1984	0.489
General cargo ship	20,000 DWT and above	DWT	31948	0.792
	less than 20,000 DWT	DWT	588	0.389
Refrigerated cargo carrier		DWT	4600	0.557
Combination carrier		DWT	5119	0.622
LNG carrier	100,000 DWT and above	DWT	9.827	0.000
	65,000 DWT and above, but less than 100,000 DWT	DWT	14479E10	2.673
	less than 65,000 DWT	65,000	14779E10	2.673
Ro-ro cargo ship (vehicle carrier)	57,700 GT and above	57,700	3627	0.590
	30,000 GT and above, but less than 57,700 GT	GT	3627	0.590
	Less than 30,000 GT	GT	330	0.329
Ro-ro cargo ship		GT	1967	0.485
Ro-ro passenger ship	Ro-ro passenger ship	GT	2023	0.460
	High-speed craft designed to SOLAS chapter X	GT	4196	0.460
Cruise passenger ship		GT	930	0.383

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