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Decarbonizing shipping in ice by intelligent icebreaking assistance: A case study of the Finnish-Swedish winter navigation system

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ABSTRACT

Ice often complicates shipping in extremely cold regions, leading to energy-consuming, expensive transportation. Ship performance can be significantly improved with icebreaking assistance that uses specialized ships called icebreakers to create navigable pathways in ice fields. Icebreakers are a critical and expensive resource with high energy consumption that must be judiciously utilized for efficient traffic flow. Optimizing icebreaker usage requires careful consideration of multiple factors related to weather, ships, and regulations. The existing decision support tools for icebreaker management primarily aim to minimize the total waiting time of ships, which may result in allocation of excess icebreakers. The paper presents a novel simulation-based approach for decarbonizing shipping in ice by intelligent icebreaking assistance. The proposed approach optimizes icebreaker assistance for both eco- and cost efficiency, allowing for more sustainable icebreaking policies. A case study representing a simplified configuration of the Finnish-Swedish Winter Navigation System demonstrates this approach to come up with alternate operating strategies that can significantly improve the emission and/or cost (e.g., up to 7 percent less greenhouse gas emission or up to 14.2% lower costs). Results show that the proposed approach is promising, for providing recommendations on environmental and economic policies to decarbonize the Finnish-Swedish icebreaking assistance.

1. Introduction

Maritime transportation is of utmost importance for global trade. According to the United Nations (UNCTAD, 2022), more than 80 percent of traded goods are carried by sea. Ships encounter diverse challenges on their way (e.g., difficult weather conditions, dense ship traffic, navigational obstacles) depending on the vessel mission and region of operation. Shipping is particularly challenging in extremely cold regions, with a high probability of a ship encountering ice on its way in a cold season, which undermines the safety and efficiency of transportation (Li et al., 2020; Dobrodeev and Sazonov, 2018; Kujala et al., 2019). Ice-related challenges can be managed in two ways: by building strong and powerful vessels with their own high icebreaking capabilities or by providing efficient icebreaking assistance. Both options have their prospects and constraints (Kondratenko et al., 2023), and selecting a specific way depends on the employed key performance indicators (KPIs) and conditions of the studied region, such as ice conditions (i.e., ice characteristics specified for spatial and temporal dimensions), ship traffic (i.e., number of vessels, their characteristics, and specific routes) and available resources (i.e., number of icebreakers, their characteristics, and the principles of operation).

Icebreaking capabilities of the ships, represented by their ice class (i.e., ship "strength" or, in other words, structural resilience), the power plant capacity, and their correspondence with the ice conditions significantly affect the requirements of icebreaking assistance. If vessels are highly capable for the targeted ice conditions, they can operate most of the route independently, using icebreaking assistance in areas with the most challenging ice conditions. That strategy is dominating the Northern Sea Route in the winter-spring season (Topaj et al., 2019), where ice conditions are severe, ship traffic is limited, and icebreakers are contracted in advance individually.

If vessels have limited icebreaking capabilities for the targeted ice conditions and mainly operate in open water, they require icebreaking assistance in most ice-covered areas of the route. That is common in the

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Gulf of Bothnia in the winter-spring season with high-density ship traffic and the Northern Sea Route in the summer-autumn season. The Finnish-Swedish Winter Navigation System (FSWNS) contains a pool of icebreakers that operates in a centralized manner in the Gulf of Bothnia and assists the popular routes. Individual icebreaking assistance for each vessel is not guaranteed but is provided according to the practices of the FSWNS operations based on the ice conditions. Although the icebreaker assistance fee is not directly paid to Finnish and Swedish organizations providing icebreaking assistance, it is included in the fairway fee collected by the government, and it depends on the ice class (for the Finnish authorities only) and the size of the assisted vessel. According to Baltic Icebreaking Management (2020), the average total cost of operation of one icebreaker in the 2019–2020 navigation season was 4.91 million euros per month, where about 11 percent is paid for fuel. Assuming the corresponding average marine fuel price was 350 euros per ton, the average icebreaker consumes more than 1200 tons of fuel per month. The corresponding CO_2 emission is significant and can be estimated at 3780 tons per icebreaker per month, assuming the conversion factor equals 3.15 (IMO, 2018).

The existing research on icebreaking assistance modeling and optimization is limited. Typical KPIs for the efficiency of icebreaker assistance are the average total waiting time – the time a vessel waits to receive icebreaker assistance (Lindeberg et al., 2018; Bergström and Kujala, 2020;Kulkarni et al., 2022a) and the total cost (Topaj et al., 2019; Kondratenko et al., 2021) of voyages of the assisted ships and icebreakers.

Sustainability can be achieved by supporting its three components: the economic, the environmental, and the social. The existing literature (Lindeberg et al., 2018; Bergström and Kujala, 2020; Kulkarni et al., 2022a; Kondratenko et al., 2021) studied the economic and social components of sustainability in the optimization of icebreaking assistance (e.g., by employing cost- and time-related KPIs). In these works, the environmental component is not considered, an issue that can be identified as a research gap. Supporting the environmental component of sustainability is currently a top priority of the International Maritime Organization and the European Union, both of which released policies to reduce greenhouse gas (GHG) emissions from ships drastically by at least 50 percent by 2050 (see Pape, 2020).

Naturally, the employed KPIs significantly affect the outcome of the icebreaking assistance optimization. Thus, minimizing the total waiting time of transport vessels for icebreaking assistance (Kulkarni et al., 2022a; Lindeberg et al., 2018; Bergström and Kujala, 2020) searches for a strategy to maximize the performance of the limited icebreaker resources by all means. However, that strategy may overuse or misuse the icebreaker resources, resulting in additional emissions and costs.

Minimizing the total cost of the system operation (Topaj et al., 2019; Kondratenko et al., 2021), i.e., the cost of time charter and fuel for all considered transport vessels and icebreakers, is a more moderate strategy, as the icebreakers are used actively only if the corresponding savings is higher than the corresponding cost. Although emissions are indirectly considered in the fuel cost, their minimization is only prioritized if it is income-generating. The assistance of the most expensive vessels is prioritized, somehow minimizing emissions, as those vessels are usually the largest and most fuel consuming.

Minimizing the total emissions of the system, i.e., the fuel-related GHG emission for all considered transport vessels and icebreakers, is an eco-friendly strategy, as icebreakers are used if emissions of their use are less than the corresponding emission reduction from ships. However, optimizing the total emission KPI is not always realistic, as the emission reduction is achieved at any cost. Thus, combining the total cost of the system operation and the total emissions of the system as optimization KPIs contributes to sustainable decision-making.

The eco-friendly strategy requires reliable methods to predict the open water and ice-going performance of transport vessels and icebreakers, and the contradicting nature of those qualities must be considered (von Bock und Polach et al., 2015). Realistic estimation of vessel energy consumption and speed profile dynamics is significant for calculating GHG emissions (Kondratenko et al., 2021; Esmailian and Steen, 2022). For any strategy of icebreaker assistance optimization, it is important to consider existing practices applied in the region and constraints of an icebreaker assistance system, e.g., performance limitations of icebreakers, their number in a specific area, and the operational logic. From the perspective of a shipping company, optimizing the performance is especially relevant for centralized icebreaking assistance where the service of a specific vessel may not be guaranteed. All these aspects combined can be effectively studied using simulation as a platform for optimization.

Acknowledging the existing challenges, we propose a new simulation-based approach to improve the existing Finnish and Swedish icebreaking policies and management practices by optimizing the performance of the FSWNS for eco- and cost-efficiency.

The remainder of this paper is structured as follows. Section 2 describes the general structure and operation principles of the FSWNS and discusses the existing approaches for its simulation. Section 3 presents the developed approach for modeling the FSWNS. Section 4 describes the methods used to estimate eco-and cost-efficiency KPIs for the FSWNS. Section 5 demonstrates the functionality of the developed approach in a case study, followed by a discussion of the results and conclusions.

2. The Finnish-Swedish winter navigation system and approaches for its simulation

2.1. The general structure and operation principles of the FSWNS

Icebreaking assistance of the FSWNS in the Gulf of Bothnia (see Fig. 1) is based on cooperating Finnish and Swedish icebreaker fleets (Finnish Transport Infrastructure Agency, 2021), serviced by the joint online decision support system IBNet. The Finnish and Swedish icebreaker fleets consist of 8 and 7 specialized ships, respectively (Finnish Transport Infrastructure Agency, 2021). The actual number of operating icebreakers for a specific year depends on the ice conditions (BIM, 2020; BIM, 2021). These icebreakers are distributed among the operating zones, and the number, location, and area of these zones may differ for different years. Besides breaking the ice, the icebreakers

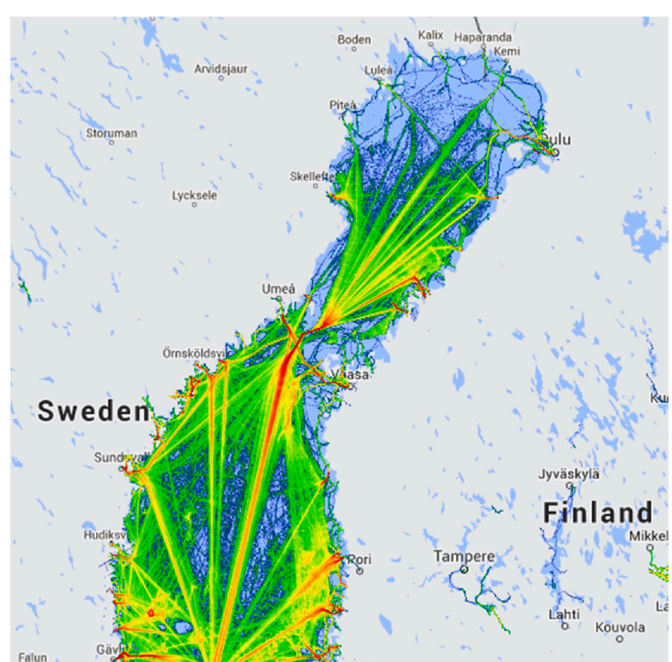

Fig. 1. The main shipping routes in the Gulf of Bothnia (Marine traffic, 2022).

coordinate the ship traffic in the corresponding zone, providing the safe waypoints forming the dirways (i.e., directed pathways) through the most favorable ice conditions, usually through the ice channels. Following the dirways helps the vessel to navigate independently for as long as possible, calling for icebreaking assistance only in the most challenging ice (Finnish Transport Infrastructure Agency, 2021). Generally, an icebreaker tows a ship if individual navigation is unsafe or inefficient. Towage is performed without additional payments. Navigating outside the dirways may cause delayed assistance if the vessel is stuck and calls for the icebreaker.

The Finish Transport Infrastructure Agency (FTIA) regularly issues port-specific requirements for the minimum ice class and the deadweight of vessels that are eligible for icebreaker assistance. All requirements applied in the 2021–2022 icebreaking season in different ports are combined in Table 1. The requirements for a specific port change during the year and significantly depend on the severity of the winter.

The ice class guarantees the minimum ship hull strength and propulsion power required to navigate in a fresh ice channel or thin ice independently. In practice, if a vessel is not eligible for icebreaking assistance, it is also not recommended to enter the port region due to safety concerns. All eligible vessels are assisted with equal priority except vessels in danger and vessels critical to emergency supply, both of which have higher priority.

The Finnish Meteorological Institute provides daily ice information support for the FSWNS, including data on the prevailing ice conditions, the operating zones of icebreakers, and dirways. FTIA provides the requirements for vessels to be eligible for icebreaking assistance in specific regions. The shipping companies must regularly submit information on voyages of vessels entering the FSWNS into the specialized PortNet system. That data is further used in icebreaker decision-making.

2.2. The existing approaches for the FSWNS simulation

The existing approaches for the FSWNS simulation are primarily developed to estimate and improve the efficiency of icebreaking assistance. The early study (Nokelainen et al., 2004) considers the FSWNS ship traffic and includes advanced models for ship performance in ice (e.g., navigating independently and with icebreaking assistance). However, Lindeberg et al. (2015) argue that icebreakers in the approach (Nokelainen et al., 2004) are not directly considered as a part of the FSWNS ship traffic, and their performance model is based on many general simplifications. Icebreaker operations are not individually modeled but accounted for using adjusting coefficients for semi-empirical and empirical equations. Such a model is more straightforward to develop than the more advanced counterparts (e.g., Bergström and Kujala, 2020; Kulkarni et al., 2022a), but these simplifications significantly limit the number of variables in the sensitivity analysis. Furthermore, any adjustment of the approach logic requires all the general simplifications to be reformulated.

Lindeberg et al. (2015, 2018) developed a detailed deterministic simulation approach, reproducing the ship traffic and icebreaker decision-making. The approach incorporates models estimating vessel performance in ice for different regimes, e.g., independent navigation in level ice and brash ice, icebreaker-assisted navigation in convoy, and towed mode. The network of the FSWNS shipping routes in the approach of Lindeberg et al. (2015, 2018) is made of building blocks – combinations of linear segments — that also determine operating zones of icebreakers. As the dirways of the FSWNS change in time, the approach supports different versions of the route networks with transition building blocks, allowing the vessel to migrate between the networks. Acknowledging the prospects of the approach, Lindeberg et al. (2015, 2018) note that it is excessively time-consuming. Another constraint of it is limited visualizing capabilities, resulting in issues while verifying and interpreting the simulation outcomes.

Bergström and Kujala (2020) proposed a stochastic hybrid approach for the FSWNS simulation based on a combination of Time-Based and Event-Based Components. Besides the total waiting time of transport vessels for icebreaking assistance, the approach estimates the FSWNS transport capacity and the number of instances of icebreaker assistance. It is noted that the simulation time of the approach is significantly shortened compared to the method of Lindeberg et al. (2015, 2018).

Unlike discrete-event models, which are based on Event-Based Components, the hybrid model allows changing the parameters of the environment with a specific time step inside the event. The simulation model proposed in Bergström and Kujala (2020) is composed of predefined blocks representing particular events. Ships navigate along the sections of the route with specific ice conditions changing in time.

Unlike the deterministic approach developed by Lindeberg et al. (2015, 2018), the Bergström and Kujala (2020) model studies the uncertainty of ice conditions, assuming them as normally distributed. Due to the limitations of the approach, the behavior of the icebreakers is simulated indirectly, using the conveyor-like event component, considering the icebreakers as resources. The time necessary to deliver the icebreaker for the assistance mission after finishing the last task is assumed to be exponentially distributed. However, it is unclear how the real distributions of parameters of ice conditions, the transfer time, and the probability of a brash ice channel correspond to the assumed distributions, as such validation is not provided.

Kulkarni et al. (2022a) proposed a decision-support approach to improve the performance of the FSWNS, combining agent-based and discrete-event simulation. The approach revises the method of Lindeberg et al. (2015, 2018) to enhance its flexibility, computational efficiency, and usability. The behavior and performance of individual entities (agents) such as transport vessels, icebreakers, ports, routes, and ice conditions are modeled individually per specific rules, formulas, and algorithms based on existing theoretical and practical knowledge of the FSWNS (see Kulkarni et al., 2022a). The estimated performance of the FSWNS is the result of the interaction of multiple agents. The stochastic discrete-event elements of the approach simulate port operations of transport vessels and icebreakers.

The approach does not require generalized assumptions as the behavior of any agent can be adjusted independently and thus has more flexibility than the earlier approaches. Like Bergström and Kujala (2020), the approach has significantly improved computational efficiency compared to the method of Lindeberg et al. (2015, 2018). Furthermore, it provides enhanced usability, supported by user-friendly visualization of the simulation and automatic reading of the FSWNS ice conditions for a specific route from a digital ice chart with high temporal and spatial resolution.

Considering the benefits of the latter approach, the present study extends it to account for eco- and cost-efficiency KPIs, supporting sustainable shipping in ice by intelligent icebreaking assistance. The provided case study applies the approach for the Finnish-Swedish winter navigation system.

Table 1
The requirements for vessels to be eligible for icebreaking assistance used in Finland in the 2021–2022 icebreaking season (adapted from Finnish Transport Infrastructure Agency, 2021).

Short name	The minimum assisted ice classes and deadweight
II 1300	II: deadweight 1300 dwt
II 2000	II: deadweight 2000 dwt
IB 2000/II 3000	IB: deadweight 2000 dwt or II: deadweight 3000 dwt
I 2000	IC: deadweight 2000 dwt
IB 2000	IB: deadweight 2000 dwt
IA 2000	IA: deadweight 2000 dwt
IA 4000	IA: deadweight 4000 dwt

3. The framework for the simulation of the Finnish-Swedish winter navigation system

3.1. The general principles of the framework

This section briefly describes the simulation approach and framework based on the method of Kulkarni et al. (2022a), which is extended in this work to account for the eco- and cost-efficiency KPIs. Fig. 2 shows the main elements and organizational principles of the framework, which is implemented using the Anylogic® software. According to the multi-level simulation approach (Delbrugger et al., 2019), environmental and traffic details of the FSWNS are modeled on separate layers called "levels." Each level can function independently and can be run as an individual simulation.

The level *Environment* captures the details of the environmental aspects of the system, which include geographical coordinates (latitude-longitude) and ice information (ice concentration, thickness, and pre-calculated equivalent ice thickness). The level *Traffic flows* models the movement of vessels and icebreakers following their itineraries, specified based on historical AIS data.

The two levels are linked using vessel-specific h-v curves – polynomial expressions determining the attainable vessel speed in ice with specific equivalent ice thickness. The h-v curves are defined for different power outputs as described in Kulkarni et al., (2022a). The speed of icebreakers and transport vessels changes in response to the ice conditions they encounter during their journey. The model uses a combination of discrete-event and agent-based simulation paradigms to capture the dynamics of maritime traffic flows, ice conditions, and their interaction. The performance of transport vessels and icebreakers is calculated assuming constant propulsion power (for example, 85% of the available propulsion power). It is noted that in practice, icebreakers adjust the propulsion power dynamically to fit their operational needs.

The spatial ice conditions are represented by latitude-longitude coordinates and are mapped to a row (r) -column (c) grid. Each cell on the grid (r, c) is an agent in the model, characterized by the ice properties of the corresponding point of the map. The ice properties are continuous in time and are updated every virtual day. The source of the ice information is the historical ice charts provided by the Finnish Meteorological Institute (FMI, 2023). Each cell is colored in a shade of blue, whose darkness is proportional to the equivalent ice thickness, defined as the total ice volume divided by its area (see Milaković et al., 2020).

Fig. 3 shows the ice state on February 1st, 2018, in the northern region of the Bay of Bothnia, visualized by the simulation model. An example of an actual ice chart from the studied period is presented in Fig. of the Appendix.

The vessels in the model move along the dirways created by icebreakers in the ice fields. The dirways are also dynamic and may be updated several times during winter, depending on the ice conditions. The dirways in the model are updated every virtual week. This frequency can be adjusted for different winter conditions, considering their dynamics. The dotted lines in Fig. 3 show the dirways. The vessels and icebreakers are modeled as agents guided by state charts, determining how they respond to runtime events (see Kulkarni et al., 2022a).

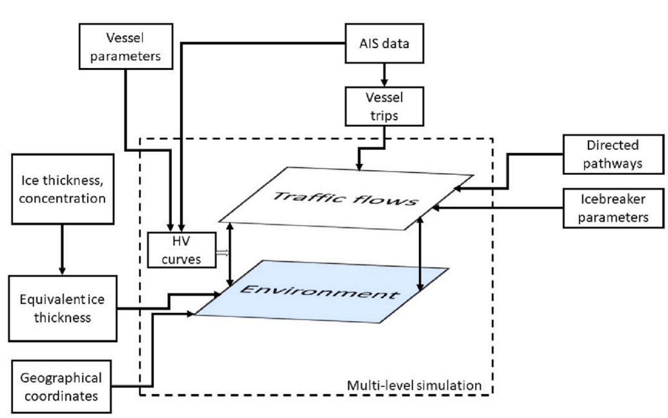

Fig. 2. The organizational scheme of the modeling framework for the Finnish-Swedish winter navigation system (Kulkarni et al., 2022b).

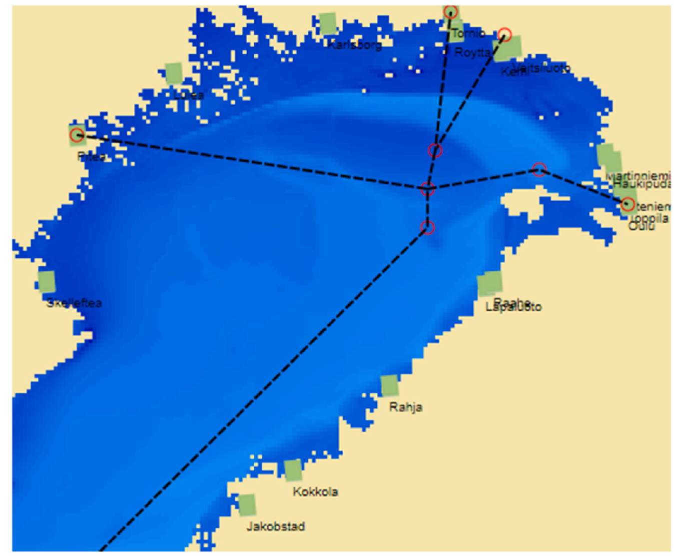

Fig. 3. Ice condition in the Bay of Bothnia, as shown in the simulation model. The lines show the dirways, and the circles show the dirway connections and ports.

The model has been initially developed with the KPI of the average total waiting time. The present study extends the framework by creating additional KPIs for eco- and cost-efficiency. The fuel consumption rate is calculated regularly for each transport vessel and icebreaker, as described in Section 4. This rate depends on the engine power used by the vessel.

3.2. Icebreaker decision-making

The operation logic of icebreakers significantly influences the FSWNS performance, e.g., the total waiting time, eco-, and cost-efficiency. While vessel itineraries (origin and destination of trips) are governed by historical AIS data, the icebreaker trips are dynamic, resulting from a series of responses to runtime events. The icebreaker decision-making aims to minimize the total waiting time of transport vessels for icebreaking assistance in the operating zone. Each icebreaker is responsible for all vessels within its operating zone and vessels entering the operating zone within a specific time horizon. A vessel requests icebreaker assistance when it cannot independently maintain the minimum required speed (3 knots is assumed in the model as the initial value). In the model, icebreakers may receive multiple assistance requests simultaneously and prioritize the vessel with the longest waiting time.

Fig. 4 shows an example of two operating zones for winter 2018. These zones are more of a recommended guideline than strict regulation – in practice, icebreaker captains work in close coordination with each other. An icebreaker may help other icebreakers if ship traffic in different operating zones is more significant than in its zone.

Three kinds of icebreakers are available to Finnish and Swedish authorities: classes A, B, and C. Class A icebreakers are the widest, with the highest icebreaking capacity, while class C icebreakers are the smallest. Since the ice is thicker up north, closer to Oulu, Kemi, and Tornio ports, the more capable icebreakers are more frequently assigned to the northern region.

In practice, icebreaker decision-making is based on the experience of

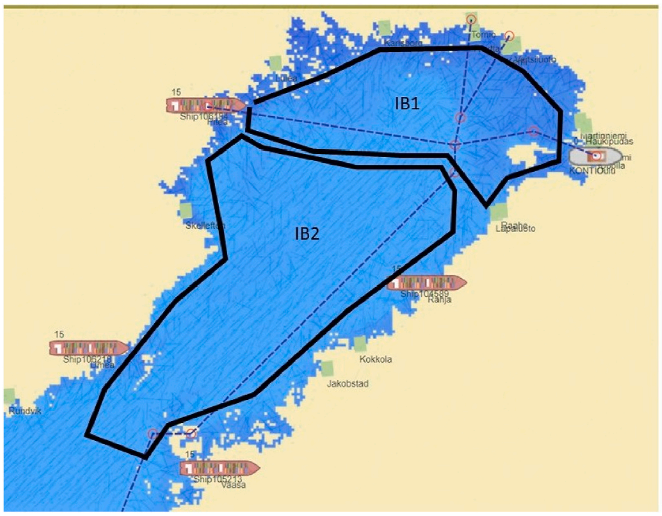

Fig. 4. Zones of icebreaker assistance in the Bay of Bothnia assumed in the model.

the captains. The captains decide which vessel(s) to prioritize based on satellite images of ice conditions and expected traffic movement in the next few hours (typically 8–12 h). The icebreakers may make certain vessels wait to combine assistance trips and reduce the total waiting time in the system.

In the current version of the simulation framework, a simplified icebreaker decision-making approach is employed. The steps involved are as follows:

1. Each icebreaker maintains a list of assistance requests received in their zone.
2. The icebreaker assists the vessel that has been waiting for the longest.
3. The icebreaker checks if any other vessel can be assisted along with the chosen vessel as part of a convoy.
4. The chosen vessel or the potential convoy is assisted until the end of the operating zone to the closest safe stopping waypoint.
5. The icebreaker updates its list of vessel requests and chooses the next vessel to assist.
6. If an icebreaker is not busy, it may assist vessel requests belonging to a neighboring operating zone of another icebreaker.

4. Materials and methods: estimation of the eco- and cost-efficiency of the Finnish-Swedish winter navigation system

4.1. The eco-efficiency and the cost-efficiency KPIs

The eco-efficiency KPI (see Eq. (1)) estimates the total CO_2 emissions (tonnes) of the FSWNS for all considered transport vessels and icebreakers. Unlike the voyage emissions, the port emissions are insignificant and cannot be affected by icebreaking assistance; consequently, they are not considered in Eq. (1). The total CO_2 emissions are calculated for the scheduled voyages of transport vessels and all simulated assistance operations of the icebreakers.

$$CO_2\ emission = \sum_{n=1}^{n_{max}} \sum_{t=1}^{t_{max}} \Delta t' C_f \left(\frac{P_d SFC_1}{\eta_{tr}} + \frac{P_{hl} SFC_2}{\eta_{hl}} \right), \tag{1}$$

where $n = 1,..,n_{max}$ is the number of transport vessels and icebreakers in the FSWNS, $t = 1.t_{max}$ is the number of the simulation period. The duration of the simulation period $\Delta t'$ (hours) is equal to the specific predefined value (i.e., the time step Δt) or less if a new simulation period is triggered. The trigger is associated with the external circumstances changing the propulsion power in use P_d (kW). $C_f = 3.15$ is the conversion factor between fuel consumption and CO_2 emission (see IMO, 2018). P_{hl} is the hotel load (kW, i.e., the power required for non-propulsion power consumers of a ship). SFC_1 and SFC_2 are the specific fuel consumptions (t/kWh) for the main engine and the electric generator. η_{tr} is the power transmission efficiency for propulsion, assumed to be equal to 0.98 for the shaft and 0.87 for the electric transmission. $\eta_{hl} = 0.93$ is the power transmission efficiency for the hotel load.

The cost-efficiency KPI (see Eq. (2)) estimates the total cost of the FSWNS operation for a specific set of vessel voyages.

$$Cost = \sum_{n=1}^{n_{max}} \sum_{t=1}^{t_{max}} \Delta t' \left(R_n + C_{fuel} \left(\frac{P_d SFC_1}{\eta_{tr}} + \frac{P_{hl} SFC_2}{\eta_{hl}} \right) \right), \tag{2}$$

where R_n is the time charter rate (USD/hour) of a transport vessel or an icebreaker, $C_{fuel} = 700$ is the fuel price (USD/t).

The specific fuel consumption SFC_1 is approximated per Eq. (3) as a function of the relative engine power in use for low-speed engines (300 revolutions per minute (RPM) or less) and medium-speed engines (300–1000 RPM) based on the data from Marques et al. (2019) and Wärtsilä (2021). Separate consideration for low-speed engines and medium-speed engines is provided to account for their differences in efficiency at part load (i.e., when power in use is less than 100% MCR). The results of the approximation for the dimensionless specific fuel consumption $\left(\frac{SFC_1}{SFC_{1,0}}\right)$ are presented in Fig. 5.

$$SFC_1 = SFC_{1,0} \left(k_1 \left(\frac{P_d}{\eta_{tr} MCR} \right)^2 + k_2 \frac{P_d}{\eta_{tr} MCR} + k_3 \right) \tag{3}$$

where $SFC_{1,0}$ is the specific fuel consumption corresponding to the maximum continuous rating of an engine MCR (kW), and $k_{1..3}$ are empirical coefficients, presented in Table 2.

The installed electric generator corresponds by design to the hotel load typical for a specific vessel, which is assumed to change insignificantly during the voyage. Therefore, the specific fuel consumption of the electric generator SFC_2 is assumed to be constant ($220*10^{-6}$ t/kWh).

4.2. Estimating the hotel load of a vessel

The hotel load may accumulate a significant share of the total fuel consumption of a ship (Rawson and Tupper, 2001), especially at low speed and while waiting for icebreaker assistance. Its value mainly depends on vessel type, size, and capacity. In the present study, the hotel

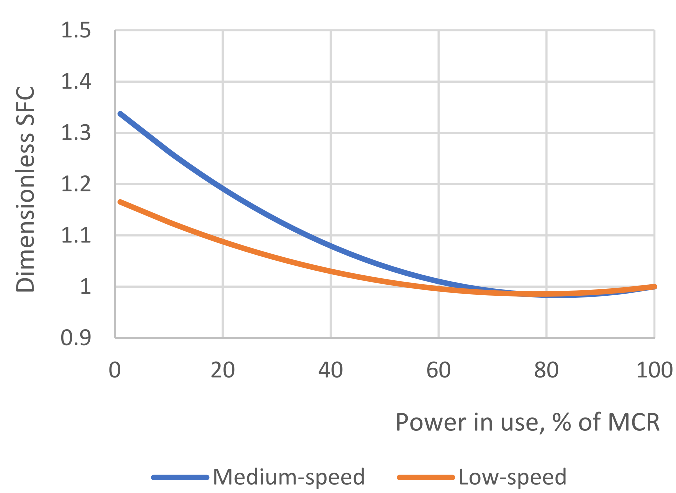

Fig. 5. The approximation results for the dimensionless specific fuel consumption $\left(\frac{SFC_1}{SFC_{1,0}}\right)$, calculated as a function of the relative engine power in use (percent of MCR).

Table 2
The approximation coefficients for Eq. (3).

Engine type	k_1	k_2	k_3
Low-speed	0.3	−0.47	1.17
Medium-speed	0.534	−0.88	1.346

load is calculated per Eqs. (4)–(9) according to the statistical method by CNIIMF (1990), based on real-life long-term onboard observations.

$$P_{hl} = P_g + P_h + P_{cpp} + P_c + P_r, \tag{4}$$

where P_g is the hotel load for general needs, P_h is the power for heating the cabins and crew working areas, P_{cpp} is the power for the pitch changing of a controllable pitch propeller, P_c is the power for heating and lighting of car decks, P_r is the power to supply refrigerated containers. P_g and P_h are considered for all vessels; however, other elements of Eq. (4) are considered only if relevant.

$$P_g = 46 \bullet 10^{-3} MCR + 33 \ \ if\ MCR < 9000 \ \ kW, \tag{5.1}$$

$$or\ 13 \bullet 10^{-3} MCR + 330\ otherwise, \tag{5.2}$$

$$P_h = 9 \bullet \sqrt{Displacement \bullet 10^{-3}} + 20, \tag{6}$$

$$P_{cpp} = 8.5\left(MCR \bullet 10^{-3}\right)^{0.4}, \tag{7}$$

$$P_c = \frac{2.16\ Displacement}{1025} + 2.25\left(\frac{2Displacement}{1025}\right)^{0.8}, \tag{8}$$

$$P_r = 3TEU_r, \tag{9}$$

where TEU_r is the ship capacity to arrange refrigerated containers, measured in a Twenty-foot Equivalent Unit.

5. Sensitivity analysis: the impact of the FSWNS parameters on the eco- and cost-efficiency KPIs

The case studies are based on historical AIS traffic data and ice data corresponding to one month of winter 2018 (15 Jan – 15 Feb) – an average winter from traffic and ice perspectives. Ice data is provided by the Finnish Meteorological Institute (FMI) (FMI, 2023). According to FMI, the winter with average ice conditions in the Baltic Sea occurred in 43 percent of cases from 2000 to 2023 and 31 percent from 2010 to 2023. Following the resolution A.1106 (29) (IMO, 2015), the AIS traffic includes voyages of all passenger ships, ships making international voyages with the gross tonnage of 300 or higher, and other vessels with the gross tonnage of 500 or higher. Two icebreakers are assumed to serve the traffic in the assigned operating zones (see Fig. 4).

Acknowledging that the raw AIS data is fragmented and sometimes includes erroneous pieces of data, the AIS data is processed using a data mining method (see Liu et al., 2022). The retrieved data corresponds to the voyages of 181 different vessels. According to the data, the total voyage time in the region for a specific vessel is significantly less than one month and variates from several hours to several days.

The technical parameters (e.g., h-v curve and the vessel parameters from equations (1)–(9)) of each vessel, necessary to calculate its performance, are determined by mapping to the closest description of the predefined vessel type (see Table 3), considering its purpose, size, and MCR. The predefined vessel types are selected as the most typical, considering long-term vessel traffic in the Gulf of Bothnia. The technical vessel data is combined from various sources, e.g., AIS records, the open-source database (BalticShipping.com, 2023), and engine documentation. The propulsion power in use for icebreakers is set to be 100%, which may differ from the existing practices (see Sec. 6).

The freight rate for each vessel is estimated (see the Table in the Appendix) based on the data from (Hellenic Shipping News Worldwide, 2023; VHBS, 2023; UNCTAD, 2022; BIM, 2020), considering the purpose of the vessel and its capacity (deadweight (DW) or twenty-foot equivalent unit (TEU)). The estimated daily freight rate variates widely from 4900 USD/day for small transport vessels to 43,000 USD/day for big vehicle carriers and 60,000 USD/day for icebreakers. The freight rates may not necessarily reflect the actual values for the studied vessels in the selected period and collateral industrial cost due to cargo delay.

According to the Table in the Appendix, the hotel load, calculated using the method presented in section 4.2, accounts for 3.4 to 13.4 percent of the total power consumption when moving at the maximum attainable speed and may account for a significantly higher percentage when moving at a lesser speed or waiting for icebreaking assistance. This highlights the importance of considering the hotel loads to estimate the total fuel consumption of the FSWNS reliably. Icebreakers and containerships have the lowest and the highest share of the hotel loads in the total power consumption correspondingly. The study is designed to analyze the sensitivity of KPIs (the CO_2 emission and the cost) to the classes of icebreakers in zones IB 1 and IB 2 (see Fig. 4), the number of icebreakers, the used propulsion power of transport vessels (percent of the full propulsion power), and the minimum required threshold speed of transport vessels when icebreaker assistance is needed. The calculation results are provided in Table 3, where 13 case studies are obtained by variation of the FSWNS parameters, using the default configuration (Case 3) as a starting point. Although Case 3 does not strictly represent the actual FSWNS configuration for the considered period of 2018 due to the limitations of the model (see Section 6), it is assumed to be efficient based on an expert estimate.

KPIs for the considered cases are provided in Fig. 6. According to Fig. 6, the starting configuration (case 3) is the second best in cost-efficiency but lacks eco-efficiency – it is the second worst in CO_2 emission among the considered cases. Some of the considered configurations

Table 3
The estimates of the impact of the FSWNS parameters on its eco- and cost-efficiency KPIs. The color of a cell depends on the effect on the KPI: green – favorable, yellow – moderate, grey – neutral, red – negative.

Case	Icebreaker classes (zone 1, zone 2)	Number of icebreakers per 181 vessels	Propulsion power, %	Minimum required speed, knots	Total fuel consumption, t	**CO_2 emission, t**	**Cost, USD**	**CO2 change**	**Cost change**
1	B, B	2	100	3	7107	22388	11569037	-0.7	10
2	A, B	2	100	3	7030	22144	12868217	-1.7	22
3	A, A	2	100	3	7154	22536	10553603	0.0	0
4	A, A	12	100	3	8126	25597	9055191	13.6	-14
5	A, A	4	100	3	6847	21568	11733873	-4.3	11
6	A, A	4	70	3	6957	21914	11966433	-2.8	13
7	A, A	4	85	3	6989	22016	11154545	-2.3	6
8	A, A	2	70	3	7011	22084	13849385	-2.0	31
9	A, A	2	85	3	6895	21721	12143717	-3.6	15
10	A, A	4	100	5	6951	21895	11794710	-2.8	12
11	A, A	4	100	7	6922	21804	13897080	-3.2	32
12	A, A	2	100	5	6988	22011	13077730	-2.3	24
13	A, A	2	100	7	6663	20987	14438087	-6.9	37

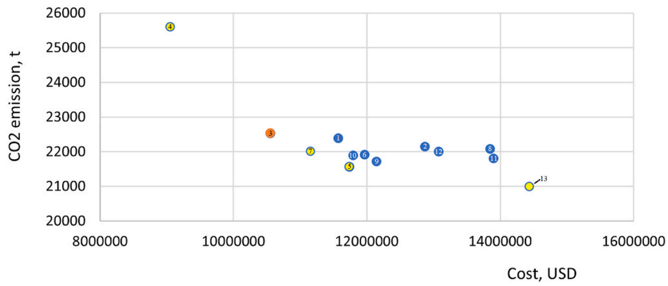

Fig. 6. The values of CO_2 emission and cost for the considered cases. The default configuration is colored orange. The other favorable tradeoffs between CO_2 emission and cost (cases 3, 4, 5, 7, and 13) among the considered solutions are colored yellow.

of the FSWNS can provide up to 7 percent less CO_2 emission (e.g., case 13) or up to 14.2 smaller costs (e.g., case 4) compared to the default configuration and up to 18 percent less CO_2 emission or up to 37 percent smaller costs compared to the worst corresponding considered configurations (cases 4 and 13 respectively). Fig. 6 demonstrates that cases 13, 5, 7, 3, and 4 are the best tradeoffs between CO_2 emission and cost, representing the Pareto front among the studied cases.

The distribution of the cost per category of expenses is shown in Fig. 7. For the studied cases, the share of fuel cost varies from 40 percent to 49 percent of the total cost of the FSWNS operation. The absolute value of the most fuel-consuming case, case 4, is 22 percent higher than that of the least-consuming case, case 13. The shares of charter costs for the icebreakers and the transport vessels vary from 11 percent to 61 percent and from 17 percent to 45 percent of the total cost, respectively. It is noted that KPIs are often antagonistic to each other in the studied cases, i.e., the FSWNS configurations with the least fuel consumption have the worst cost-efficiency, and vice versa.

Fig. 8 shows how KPIs change when the FSWNS parameters are varied. Variation of the classes of icebreakers in zones IB 1 and IB 2 (cases 1, 2, and 3, Fig. 8(a)) may result in about a 2 percent decrease in CO_2 emission by employing a more adapted allocation of the icebreakers (case 2) compared to the default configuration. In case 2, the stronger icebreaker (class A) is used in the northern part of the Bay of Bothnia with more complex ice, and the weaker icebreaker is used in the southern part. However, the 2 percent CO_2 emission decrease comes at a 22 percent higher cost due to prolonged voyages of the transport ships and the icebreakers.

Increasing the number of icebreakers by 2 (see Fig. 8(b)) (cases 3 and 5) demonstrates a significant reduction of CO_2 emission by 4.3 percent (case 5), which results in an 11 percent higher cost. Employing other

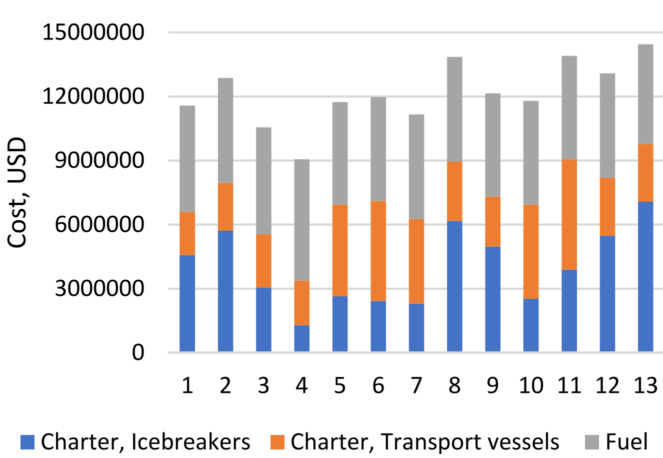

Fig. 7. Distribution of the cost per the categories of expenses for case studies from 1 to 13.

additional icebreakers (case 4) causes 13.6 percent higher emissions and a 14.2 percent cost reduction compared to case 3 due to savings of time and the corresponding charter costs of the transport ships and the icebreakers.

Another critical parameter to analyze is the default propulsion power of transport vessels. As demonstrated in Fig. 8(c), using 85 percent of the installed propulsion power (case 9) results in a 3.6 percent reduction of CO_2 emissions compared to using 100 percent of it in case 3, which is mainly caused by more efficient engine performance (see Fig. 5). However, the emission reduction comes at a 15 percent higher cost. The data for cases 8, 9, and 3 shows that reducing the used propulsion power of transport vessels causes higher total costs, particularly because of the longer voyages and corresponding expensive charter of the transport vessels and icebreakers. A similar comparison for the cases with 4 icebreakers (cases 6, 7, and 5, see Fig. 8(d)) does not clearly demonstrate similar trends due to the deemphasized role of the transport ships and the significant share of the icebreakers in the cost and the CO_2 emission.

The last varied parameter is the minimum required speed of transport vessels, which determines how fast the icebreaking assistance is provided. The data for cases 3, 12, and 13 (see Fig. 8(e)) indicates that a gradual increase of the required speed from 3 knots to 5 and 7 knots results in significant emission reduction of up to 7 percent, with up to 37 percent higher costs. The environmental benefit is mainly associated with the reduced emission from the transport vessels (see Fig. 9). A similar comparison for the cases with 4 icebreakers (cases 5, 10, and 11, see Fig. 8(f)) demonstrates that the required speed higher than 3 knots does not reduce CO_2 emission or cost, which may be related to the oversupply of the icebreaker resources.

6. Discussion of the results and conclusions

Transportation of people and goods is the necessary driving force that keeps society moving. Maritime transportation is the “cleanest” mode of transport. However, it is complicated in extremely cold regions due to the presence of ice, resulting in higher costs and consumed energy. The rising environmental consciousness results in a trending demand for more sustainable technologies and management practices for northern maritime shipping.

Acknowledging these relevant issues, we developed a novel approach for decarbonizing shipping in ice by intelligent icebreaking assistance for a case study of the Finnish-Swedish winter navigation system (FSWNS). The authors proposed to use new key performance indicators for icebreaking assistance in addition to the traditionally employed total waiting time, namely the CO_2 emissions of the FSWNS, covering the environmental aspect of sustainability, and the cost-efficiency of the FSWNS, covering the economic aspect of sustainability. The proposed formulation helps not only to decarbonize the FSWNS but also to estimate the related costs – that is important as some potential solutions may prove to be unrealistic.

The case studies demonstrated significant potential theoretical benefits from the implications of the proposed approach from decarbonizing and cost-saving perspectives, e.g., about 7 percent less greenhouse gas emission or up to 14.2 lower costs compared to the configuration based on the actual operation practice (see Table 3, case 3). However, further development of the tool is needed before the simulation results can be applied to real situations, as some essential features of the Finnish-Swedish Winter Navigation System, listed at the end of the current section, are yet to be considered.

Based on the present study, specific theoretical recommendations on policies to decarbonize the Finnish-Swedish icebreaking assistance are formulated. Please refer to Section 5 for detailed reasoning behind the recommendations. The recommendations are valid for the given winter conditions only. A similar analysis can also be performed to obtain such recommendations for other winters. The recommendations are now listed as follows:

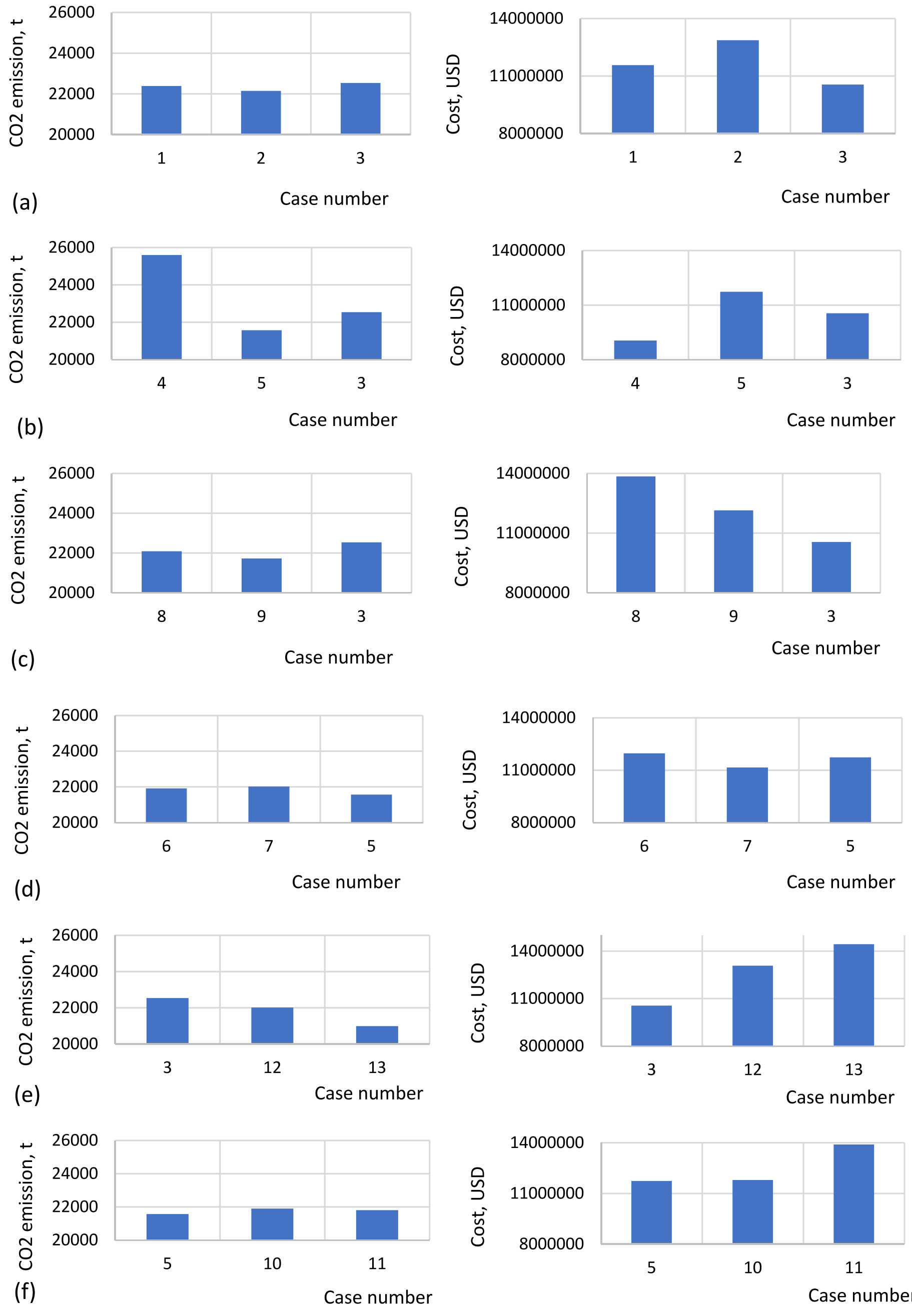

Fig. 8. The calculation results, demonstrating the CO_2 emission and the cost of the FSWNS operation for different case studies, numbered from 1 to 13.

1) Increasing the number of actively operating icebreakers in the Bay of Bothnia from 2 to 4 is recommended, resulting in a significant reduction of CO_2 emission by 4.3 percent with an 11 percent higher cost. Employing an excessive number of icebreakers (e.g., 12) is not recommended as it has no decarbonizing benefit. The number of icebreakers required depends on the intensity of weather conditions. The simulation tool can assist in running what-if scenarios to compare the FSWNS performance for different numbers of icebreakers, thereby allowing policymakers to decide on the optimal number for the given situation.
2) If two icebreakers provide icebreaking assistance (for the given winter conditions), it is recommended for the transport vessels to use 85 percent of the max installed propulsion power, resulting in a significant reduction of CO_2 emission by 3.6 percent. Using 70 and 100 percent of the maximum installed propulsion power is considered suboptimal. This results from various factors, such as the length of voyages, icebreaker trips required, and vessel waiting time. While it may be hard to manually consider all the factors, the simulation tool allows policymakers to visualize the combined effects of these factors.
3) If two icebreakers provide icebreaking assistance, the minimum required threshold speed of transport vessels is recommended to be set at 7 knots for significant decarbonizing and at 3 knots for a favorable cost-decarbonizing tradeoff. This is due to the reduced emissions from transport vehicles, which travel most of their voyages at higher speeds due to assistance at 7kn instead of 3kn.
4) If four icebreakers provide icebreaking assistance, it is recommended that the transport vessels use 100 percent of the max installed propulsion power. However, using 85 percent is also recommended as a favorable cost-decarbonizing tradeoff.
5) If four icebreakers provide icebreaking assistance, the minimum required threshold speed of transport vessels is recommended to be

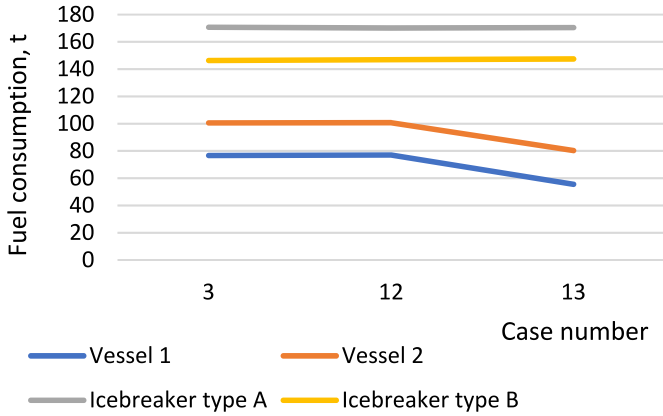

Fig. 9. The total fuel consumption of selected individual vessels – two transport vessels (1 and 2) and two icebreakers – for case studies 3, 12, and 13, where the minimum required speed is variated.

set at 3 knots. Using 5 and 7 knots thresholds is considered suboptimal. This is likely due to an oversupply of icebreaker resources.

6) Using highly capable icebreakers of class A in the northern and southern zones of the Bay of Bothnia is recommended. Replacing icebreakers of A class with icebreakers of B class results in a limited decarbonizing benefit with a high cost.

The most efficient way to reduce CO_2 emissions (up to 6.9 percent) among the considered options is using two icebreakers and providing earlier icebreaking assistance (i.e., applying the minimum required threshold speed of 7 knots), which, however, requires 5 percent higher costs for every percent of the emission reduction. The most cost-efficient way to reduce CO_2 emission is employing additional icebreakers, which requires about 2.5 percent higher cost for every percent of emission reduction. However, in that case, the maximum reduction is limited to 4.3 percent when the need for icebreaker assistance is completely satisfied. It is noted that combining several measures instead of isolated changing of one operational parameter may be favorable, as combining factors results in nonlinear changes, e.g., demonstrated for the FSWNS configurations with two and four icebreakers. After receiving feedback from the FSWNS practical experts, we found that recommendation number 3 is already considered the best practice. It is to be noted that we do not provide recommendations for the speed of icebreaking assistance but for the minimum required threshold speed of transport vessels when icebreaker assistance is needed. It is the speed when an independent ship becomes eligible to receive assistance. As for the assistance speed, the employed values are agreed upon by an experienced icebreaker captain based on regulations and ship capabilities.

Another important observation is that the hotel load, considered in the present work for the first time in the studied context, accounts for a significant part of the fuel consumption of transport vessels, e.g., up to 13.4 percent of the total power consumption when moving at the maximum speed, and up to 100 percent when waiting for icebreaker assistance. Refusing to consider the hotel load in assessing the icebreaking assistance may result in suboptimal conclusions.

The study demonstrated that the total waiting time of transport vessels for icebreaking assistance – the presently employed KPI to measure the efficiency of the FSWNS – may significantly prioritize cost-efficiency over decarbonizing. Minimizing the total waiting time makes the FSWNS, e.g., transport vessels and icebreakers, work faster, consuming more fuel, while decarbonizing solutions often take more time (e.g., slow steaming). Therefore, it is recommended for Finnish and Swedish policymakers, in addition to the total waiting time consider other KPIs (e.g., CO_2 emission and direct cost) in their decision-making. The total waiting time is assumed to be relevant as it represents the delay of goods with economic and reliability importance.

Applying operational decision-support tools like the one developed in the present research has significant prospects because it is a relatively easy way of decarbonization compared to the cost- and time-consuming development of new ship design technologies and solutions, providing similar improvements. Moreover, as demonstrated in the present study, intuitive solutions, e.g., minimizing the total waiting time of transport vessels or providing less capable icebreakers in the southern part of the Bay of Bothnia, may theoretically have higher CO_2 emissions, although improving the cost efficiency.

The recommendations demonstrate the significant future potential of the model to improve FSWNS efficiency. To make the model applicable for practical use, the following aspects will be worked on as the following steps 1) the entire winter (not just one month) and corresponding ice conditions will be considered, 2) the number of icebreakers in a specific operating zone will be modeled as a dynamic variable because it is adjusted for the changing ice conditions during the winter. 3) operating zones of icebreakers in the model will closely correspond to the applied practices of the considered period, 4) for navigational safety icebreakers and merchant vessels will be modeled to maintain some power margin, meaning that 100% of propulsion may not always be used 5) more detailed modeling of icebreaker convoys and optimizing their parameters, considering case studies with more complex, severe ice conditions, and modeling ice channels and drifting ice is recommended.

The capabilities and the efficiency of the approach can be further extended by addressing the existing mathematical limitations of the approach, namely by 1) formal optimizing of the FSWNS parameters instead of manual search, 2) formal optimizing the decision-making process of icebreakers instead of using a simplified heuristic. 3) developing more detailed cost-efficiency models.

Author contribution

Aleksander A. Kondratenko: Writing – original draft, Conceptualization, Methodology, Validation, Data curation.

Ketki Kulkarni, Writing – original draft, Conceptualization, Methodology, Validation, Visualization.

Fang Li: Methodology, Investigation, Validation, reviewing, Data curation.

Mashrura Musharraf: Writing – review & editing, Supervision, Funding acquisition.

Spyros Hirdaris: Supervision, reviewing.

Pentti Kujala: Project administration, Funding acquisition, Investigation, reviewing.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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Appendix

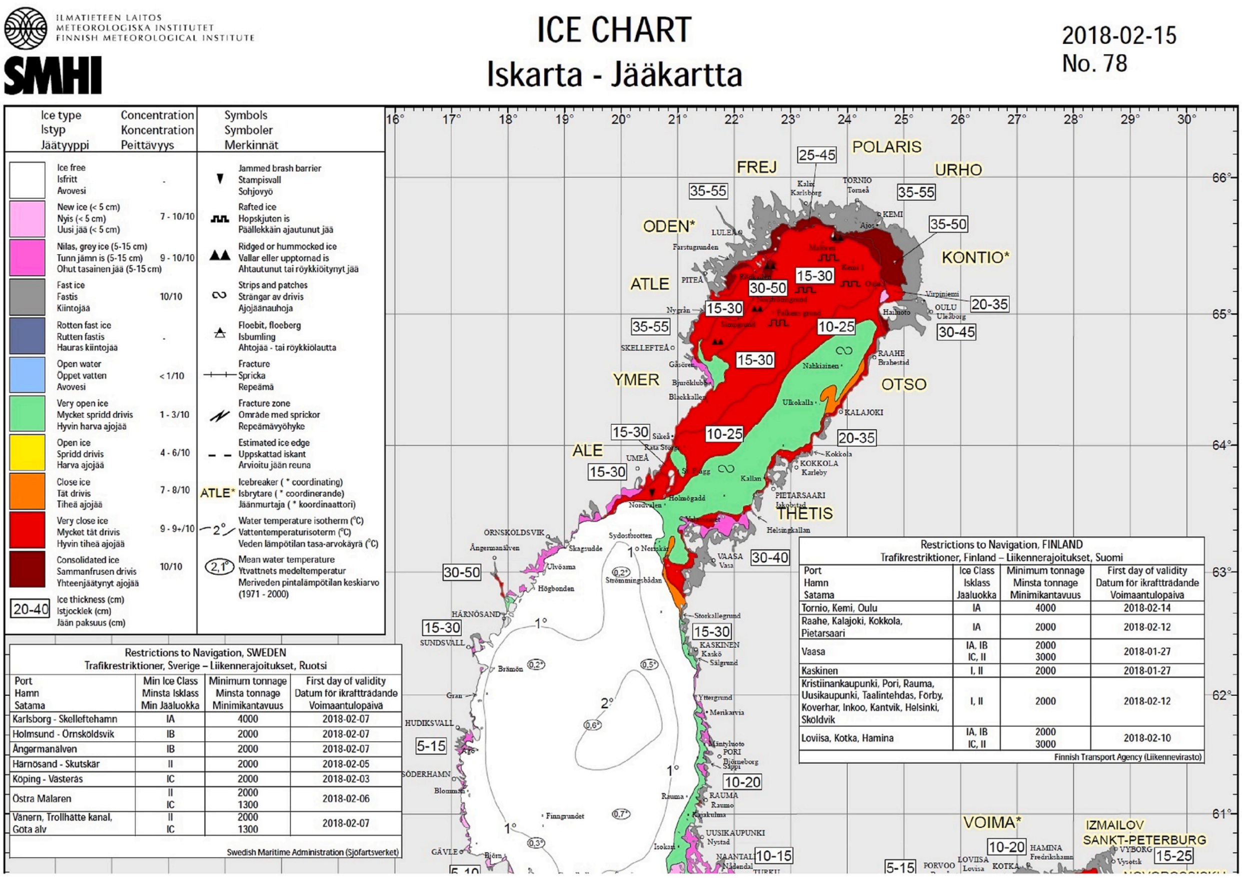

Figure. An example ice chart for the studied region.

Table
The description of pre-determined vessel types. The following nomenclature is utilized in Table: B is a bulker, BT is a bunkering tanker, CS is a containership, G is a general cargo ship, O/C T is an oil/chemical tanker, VC is a vehicles carrier, IB is an icebreaker, Δ is the displacement, DW is the deadweight, R_n is the time charter rate, $P_{d,\ max}$ is the maximum installed propulsion power, CPP is the controllable pitch propeller, FPP is the fixed pitch propeller, TEUr is the ship capacity to arrange refrigerated containers, L is the low-speed engine, M is the middle-speed engine, P_{hl} is the hotel load, and $SFC_{1,0}$ is the specific fuel consumption corresponding to the MCR.

n	Purpose	Δ	DW	R_n	$P_{d,\ max}$	MCR	Propulsion	Propeller	TEUr	Engine	P_{hl}	$SFC_{1,0}$	Ice class
1	B	65825	56348	15000	9877	9877	Shaft	CPP		L	573	170	IA
2	B	53428	43706	13000	11475	11475	Shaft	CPP		L	588	185	IAS
3	BT	11843	8000	7000	4080	4080	Shaft	CPP		M	287	175	IA
4	CS	9858	7131	8000	5300	5300	Shaft	CPP	100	M	642	175	IA
5	CS	14130	9543	7500	7999	7999	Shaft	CPP	150	M	924	177	IA
6	CS	17782	12110	10000	9600	9600	Shaft	CPP	200	M	1134	175	IA
7	CS	25868	16939	12000	12177	12177	Shaft	FPP	258	L	1328	175	IA
8	CS	25284	15956	15000	12640	12640	Shaft	CPP	312	L	1519	175	IAS
9	G	4163	3684	5100	749	749	Shaft	CPP		M	113	206	1C
10	G	3827	3171	5000	1800	1800	Shaft	CPP		M	164	187	IA
11	G	4257	3017	4900	1835	1835	Shaft	CPP		M	167	185	IB
12	G	4927	4500	5300	2640	2640	Shaft	CPP		M	207	187	IA
13	G	5888	4953	5500	2760	2760	Shaft	CPP		M	215	180	IA
14	G	8748	6796	8700	3000	3000	Shaft	CPP	20	M	291	186	IA
15	G	9331	7055	9000	3840	3840	Shaft	CPP		M	272	177	IA
16	G	16536	14595	13000	4500	4500	Shaft	CPP		M	312	185	IA
17	G	13279	7750	9300	4690	4690	Shaft	FPP		L	302	185	IAS
18	G	15418	12200	10800	4950	4950	Shaft	CPP	30	M	422	185	1A
19	G	10636	8860	9500	5280	5280	Shaft	CPP	60	M	522	183	IA
20	G	16666	12638	11000	5400	5400	Shaft	CPP	25	M	430	177	IA
21	G	10710	14595	13000	5440	5440	Shaft	CPP	60	M	529	183	IA
22	G	38149	30809	22500	7200	7200	Shaft	FPP		L	440	173	IC

(continued on next page)

Table (*continued*)

n	Purpose	Δ	DW	R_n	$P_{d,\ max}$	MCR	Propulsion	Propeller	TEUr	Engine	P_{hl}	$SFC_{1,0}$	Ice class
23	G	27338	19625	17000	7200	7200	Shaft	CPP		L	450	173	IAS
24	G	21454	14883	18200	7282	7282	Shaft	CPP		L	448	185	IA
25	G	32117	21402	18000	12060	12060	Shaft	CPP	120	M	941	185	IA
26	G	36562	23660	18500	12060	12060	Shaft	CPP	120	M	944	185	IA
27	O/C T	13167	9597	7500	4500	4500	Shaft	CPP		M	308	186	IAS
28	O/C T	14244	11340	8000	4590	4590	Shaft	CPP		M	314	175	IA
29	O/C T	6770	4700	6500	4750	4750	Shaft	CPP		M	311	175	IA
30	O/C T	23510	17000	9500	6600	6600	Shaft	CPP		M	418	175	IA
31	O/C T	18307	14665	9000	8450	8450	Shaft	CPP		M	500	175	IAS
32	O/C T	31986	25000	11000	9450	9450	Shaft	CPP		M	545	175	IAS
33	O/C T	43971	37333	12500	9488	9488	Shaft	CPP		L	554	175	IB
34	Ro-Ro	10002	5409	6000	5920	5920	Shaft	CPP		M	416	185	IA
35	Ro-Ro	19782	14447	18000	7680	7680	Shaft	CPP		M	549	185	IAS
36	Ro-Ro	16691	10100	15000	9450	9450	Shaft	CPP		M	602	185	IA
37	Ro-Ro	14375	8700	10000	12600	12600	Shaft	CPP	50	M	784	178	IAS
38	Ro-Ro	22758	16675	20000	15815	15815	Shaft	FPP		L	693	185	IAS
39	Ro-Ro	25112	13800	17500	18000	18000	Shaft	CPP		M	760	185	1AS
40	Ro-Ro	22716	10372	15000	20000	20000	Shaft	CPP	75	M	1001	185	IA
41	Ro-Ro	21476	11682	16000	23040	23040	Shaft	CPP	130	M	1201	185	IAS
42	VC	24506	12562	43000	8052	8052	Shaft	CPP		L	589	170	IC
43	VC	9160	4311	14800	9840	9840	Shaft	CPP		M	568	185	IA
44	VC	13729	7629	26100	14480	14480	Shaft	CPP		M	657	175	IAS
45	IB	9660		60000	16200	17100	Diesel-electric	CPP		M	642	175	IA Super
46	IB	10961		60000	19000	21000	Diesel-electric	FPP		M	671	185	IA Super
47	IB	9222		60000	15000	21840	Diesel-electric	FPP		M	680	185	IA Super

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