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# System-level Simulation for Sustainable Winter Navigation

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ABSTRACT: Many European countries are connected to the Baltic Sea, making it vital for transporting goods and passengers in the region. Because of its northern location, a significant part of the Baltic Sea is ice-covered in winter, resulting in complications for ship navigation. Icebreakers may allow for safe and efficient transportation in ice conditions, which requires their organizing in a centralized system aimed at efficient and sustainable navigation. It is vital to analyze maritime traffic in ice to understand better the future need for icebreakers in the Baltic Sea. The paper applies agent-based simulation to enhance the performance of winter navigation and icebreaking assistance in the Bay of Bothnia. We developed novel algorithms upgrading our decision-support tool to model the dynamics of the icebreaker resource availability, optimize icebreaker allocation in the Bay of Bothnia, and study how changing the directed pathways affects the efficiency of the winter navigation system. We demonstrated the capabilities of the developed algorithms in the case studies.

## 1 INTRODUCTION

The Baltic Sea connects all the countries in the Baltic region, including, among others, Finland, Sweden, and Estonia. The location makes its maritime routes vital in supporting reliable and sustainable transportation in Europe [1-3]. Sea ice dynamics challenges shipping in the Baltic Sea. Several countries in the region have established centralized systems providing icebreaking assistance, including the most northern Finnish–Swedish Winter Navigation System (FSWNS), maintaining safe and efficient year-round navigation in the Gulf of Bothnia [4, 5].

A typical winter navigation system (WNS) consists of ship traffic, icebreakers, and an organizing framework setting up the principles of their operation. The required icebreaking assistance (i.e., number, location of icebreakers, and their characteristics) in specific ice conditions depends on the icebreaking capabilities of the ship traffic: the less ice-strengthened the ships, the more icebreaker resource is needed. The winter navigation system is developed to guarantee safe and reliable shipping throughout the winter. It also imposes some minimum size and ice class requirements on the ships to ensure safe and efficient operations. Moreover, ships must be built and operated following the corresponding ice-class rules applied in the region [5, 6].

Climate change will affect future ice conditions, so the maximum ice extent and average ice thickness might decrease [7]. At the same time, climate change might result in more stormy winds and waves, increasing ice movements. This makes the ice more dynamic, results in a higher possibility of forming ridged ice, and makes the ice conditions more spatially heterogeneous and less predictable. Offshore wind farms affect the local ice conditions so that the typical ice patterns and related ice parameter statistics may no longer be relevant, e.g., they change the dynamics of ice development and break and redirect the moving ice [8, 9].

The size of a typical ship seems to grow in the future, and the new strict environmental regulations will decrease the engine power installed on ships. The International Maritime Organization (IMO) adopted Energy Efficiency Design Index (EEDI) regulations in 2011 to reduce the amount of greenhouse gases (GHGs) emitted by ships [10]. These regulations promote energy-efficient solutions [11] but may prioritise underpowering of fossil-fuelled ships and their optimization for open water conditions. This will decrease the ice-going capabilities of these ships dramatically and possibly will result in higher demand for icebreaker assistance. Therefore, developing system-level simulation tools that study such factors is essential to understand and reliably predict future trends.

Over the last decades, a number of studies have contributed to the topic at hand by modeling the system-level performance of winter navigation. They aim to develop [4, 12-14], upgrade, and apply [15-16] software that can be used to simulate the need for icebreakers in the future when ice conditions, maritime traffic, and characteristics of ice-strengthened ships are under dynamic change.

The present paper upgrades the method by Kulkarni et al. [4] to account for the new WNS features. This allows for a more realistic simulation of the WNS operation by considering additional practical navigation aspects not presented in [4]. Specifically, we developed the novel algorithms and prepared the input data to model the dynamics of the icebreaker resource availability, optimize icebreaker allocation in the Bay of Bothnia, and study how changing the directed pathways affects WNS efficiency. The remainder of this paper is structured as follows. Section II analyses existing approaches and models for the simulation of winter navigation in the Baltic Sea and their applications. Section III describes newly developed algorithms and input data for the case studies and demonstrates the results of thirty-six simulation experiments, followed by a discussion of the results and conclusions.

## 2 DEVELOPMENT OF SIMULATION FRAMEWORKS FOR WINTER NAVIGATION IN THE BALTIC SEA

### 2.1 *Existing approaches for simulation of the winter navigation in the Baltic Sea*

One of the early models of winter navigation in the Baltic Sea [12] considered navigation in the Bay of Bothnia, estimating the performance of independent and icebreaker-assisted ships in the ice. However, the outlook of the framework is not systemic, which limits the number of factors that can be analyzed. Lindeberg et al. [13] proposed a new systemic simulation approach, individually modeling ships and icebreakers to address this problem. The approach considered vessel performance in ice for different regimes, e.g., independent navigation in level and brash ice, icebreaker-assisted navigation in convoy, and towed mode [15]. Transport ships and icebreakers follow the network of fairways (see Fig. 1) that consist of linear and y-shaped segments whose location may change over time. The limitations of the approach are long running time and limited visualizing capabilities.

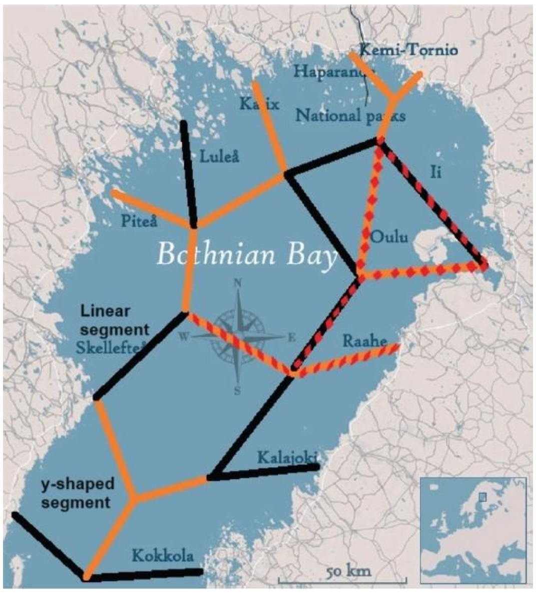


Figure 1. The fairway network implemented in the simulation approach by Lindeberg et al. [13]. It consists of the building blocks – sections (black) and junctions (yellow). The red stripes show an example of one operational area.

Bergström and Kujala [14] developed a stochastic discrete-event approach in the Simulink modeling environment for the FSWNS simulation, which can change the environment parameters with a specific time step inside the event. The discrete-event simulation allows the creation of the model from the standard building blocks – predefined templates of different events like delay, queue, service by resource, or moving. The stochastic ice parameters are defined individually for each segment of the route. The approach considered the possibility of convoy formation, with an icebreaker assisting up to two transport vessels. It allows for estimating the total waiting time of transport ships for icebreaking assistance and the transport capacity of the FSWNS for a specific period.

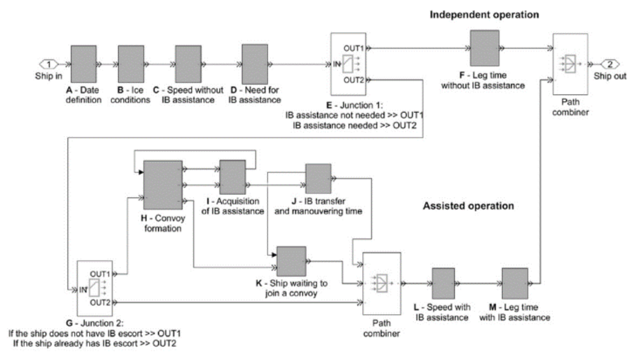


Figure 2. The flowchart of the stochastic discrete-event model of the FSWNS by Bergström and Kujala [14].

Fig. 2 shows an example of the event diagram provided in the study, where a ship is modeled as a passive entity, and an icebreaker is modeled as a limited resource. The behavior of ships and icebreakers is assigned collectively based on a specific general pattern. In other words, ordering a particular ship to move to a specific point would require changing the structure of the model, which would affect all vessels and icebreakers. The approach has high computational efficiency of the simulation, making it faster. It benefits from using stochastic parameters, as it allows the capture of complexities of nature and conducting reliability studies by assigning the confidence level to a specific conclusion.

Kulkarni et al. [4] proposed an agent-based approach developed in the AnyLogic modeling environment for the simulation of the WNS in the Baltic Sea. The approach stands out from the previous state of the art by individually modeling the behavior of the WNS elements called agents (i.e., transport vessels, icebreakers, ports, routes, ice). Thus, transport vessels and icebreakers may behave differently depending on the dynamic circumstances (i.e., environment and other agents) they encounter. This feature allows for significant modularity of the model, resulting in some benefits. Firstly, it provided great potential for analysis of how different factors of winter navigation affect system performance indicators. Secondly, modularity made the model easy to upgrade for new functionality, as the changes will only influence the corresponding modules of the model. The model has advanced capabilities for visualizing the simulation process, allowing for more accessible verification and interpretation of the results. The approach has favorable computational efficiency. An average run of a simulation model for one winter month takes from thirty minutes to one hour for the average office laptop. Considering the benefits of the approach by Kulkarni et al. [4], different studies extended the approach to account for new features and regions of application [15-16]. The present study upgrades the method by Kulkarni et al. [4] to account for the dynamics of the icebreaker resource availability and optimization of icebreaker allocation in the Bay of Bothnia and to analyze how changing the directed pathways affects the WNS efficiency.

### 2.2 *System-level simulation model for sustainable winter navigation in the Baltic Sea*

Fig. 3 shows the principle organizational scheme of the approach by Kulkarni et al. [4]. It is based on two primary model layers: Traffic flows and Environment. Traffic flows include necessary data on transport ships, icebreakers, and their operation. The definition of Traffic flows starts from processing raw Automatic Identification System (AIS) data, i.e., automatic regular reports of coordinates of the vessels with specific time intervals. The data are processed for a specific area and period into the unified information on voyages of transport vessels. The voyage data includes the Maritime Mobile Service Identity (MMSI) number of the vessel, starting and destination ports, and the time when the voyage commences and finishes. The finish time of the voyage is used to verify the estimated voyage duration by comparing it with the actual practical data. Alongside vessel location, the input traffic data include the basic vessel parameters corresponding to a specific MMSI number, i.e., vessel type (e.g., tanker, bulker, containership, Ro-Ro), ice class, the total engine power, deadweight, maximum speed in open water, and breadth. Considering that the number of merchant vessels in the traffic may include hundreds of vessels, it is often time-consuming to specify the individual technical information for every ship. For that purpose, about fifty default ship descriptions – further called ship types – are entered into the model, which includes detailed technical information on the most typical merchant vessels in the Baltic region.

The technical information includes the necessary data to model the performance of ships in ice and open water (i.e., to estimate attained speed at specific power output). For every merchant vessel, the closest default ship is selected using the basic parameters from the input data, as shown in Fig. 4. Later, in calculations, the merchant ship is assumed to be identical to the selected default ship.

The attained ship speed v in specific ice conditions is calculated based on the cubic polynomial h-v curves (see Fig. 5), where h stands for the equivalent ice thickness. The h-v curves are defined for independent operation and moving behind an icebreaker, assuming 100% power output. The h-v curves for the default ship types were developed in Project Winmos II [17-19] by Aker Arctic. When a ship is moving at a partial engine load (i.e., the power output is less than 100%), the h-v curve is recalculated assuming the speed in the limit ice proportional to power output to the 4/9 power, and the speed in open water proportional to the 1/3 power as described in Kulkarni et al. [4]. The limit level ice thickness of a ship is typically defined by conditions when it cannot move faster than from 1.5 to 2 knots. Independent navigation in thicker ice is considered unsafe and is not allowed.

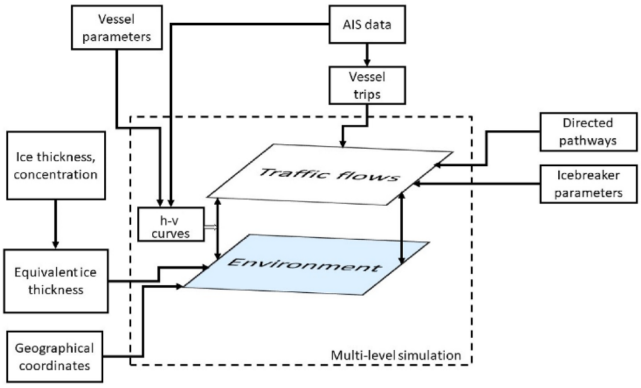


Figure 3. The organizational scheme of the simulation approach by Kulkarni et al. [4].

All icebreakers are divided into three types (A, B, and C) with specified h-v curves, where A has the most advanced icebreaking characteristics. The model allows for up to two vessels in an icebreaker convoy. The speed of the convoy is calculated as the minimum of values of attained speed for an icebreaker and assisted vessels considering their h-v curves. Convoys are moving along the directed pathways, similar to the fairway network shown in Fig. 1. In practice, authorities issue the directed pathways as recommended routes for merchant vessels, considering ice conditions, available icebreaker resources, and their allocation. The directed pathways consist of waypoints connected by linear paths. Since the voyage data are limited by starting and destination ports, the information on reaching from one port to another is stored separately for all possible combinations as a sequence of waypoints a ship passes along the way.

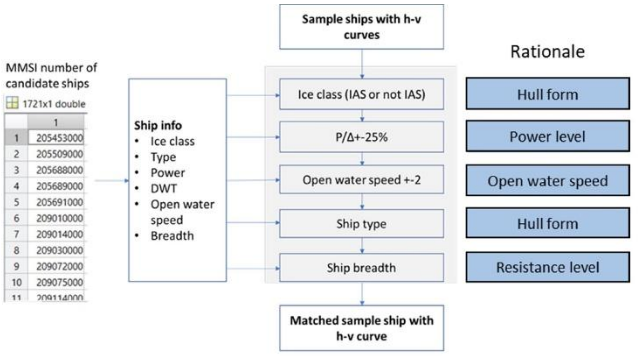


Figure 4. Mapping the merchant ship to the closest prototype ship [4].

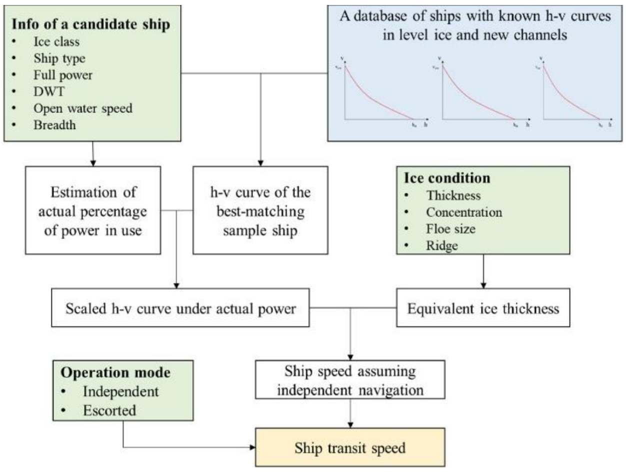


Figure 5. Estimating the ship transit speed in specific ice conditions [4].

The second model layer is the Environment, which includes a Geographical Information System (GIS) map of the studied region (see Fig. 6) with directed pathways, ports, waypoints, and ice conditions presented corresponding to their geographical coordinates. Considering that h-v curves for vessels and icebreakers are specified for level ice thickness, complex ice conditions are modeled using the concept of the equivalent ice thickness. As per this concept, the complex ice conditions with many properties (e.g., thickness, ridging, concentration, size of the ice floe) may be replaced in the model by only one characteristic – equivalent level ice thickness, assuming corresponding ship speed is the same in both complex and level-ice conditions [4].

The quality of ice data significantly affects the accuracy of simulation results. The ice information is available through ice forecast data published by the Finnish Meteorological Institute (FMI). The Environment layer is divided into cells with a geographical area of a square mile. The ice data in the model are specified for each cell with a time resolution of one day, allowing for the trade-off between calculation time and accuracy. The equivalent ice thickness is calculated as a function of concentration and thickness [4]. Besides ice data, each cell has information to which icebreaker assistance zone it belongs. The GIS map is divided into icebreaker assistance zones, allowing for allocating icebreakers based on ice conditions. One or more icebreaker zones are identified, through which the vessel will navigate to its destination. At least one icebreaker is available in each zone [20].

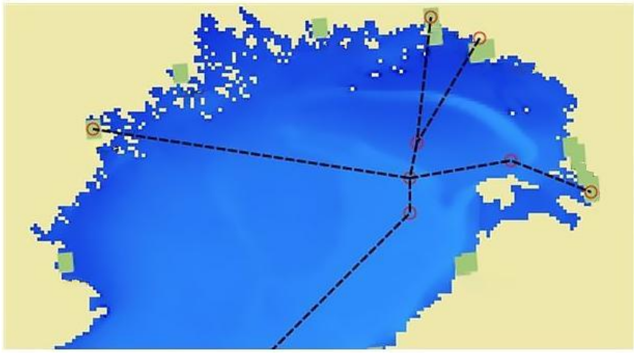

Figure 6. The GIS map of the simulation model [4]. Ice conditions are shown by different grades of blue color, where darker shades indicate thicker ice.

When the data from the Traffic flows and Environment layers are read, the voyages are simulated chronologically. The individual flow charts of agents guide the simulation. Every vessel aims to finish the voyage from the start port to the end port using the directed pathways. The speed of the vessel is recalculated every time the ice parameters change. If the vessel speed drops below a certain threshold, it requests assistance from the ice-breakers available for the relevant icebreaker assistance zone. The icebreaking assistance threshold may not be less than the limit level ice thickness of a ship specified for the h-v curve. Each icebreaker serves first the vessel that waited the longest for assistance according to the first in, first out principle. The same icebreakers may assist multiple vessels through convoys if they are headed in the same direction. The simulation ends when all vessels in the considered period have completed their schedules.

Vessels often need assistance across multiple icebreaker zones. Typically, each icebreaker guides a vessel through its operating zone, leaving it at a boundary waypoint unless the port is in the zone [20]. The next icebreaker takes over the assistance mission at the waypoint, guiding the vessel further along its navigational journey. However, icebreakers can operate outside their operating zones to ease traffic build-up or help larger vessels that need two icebreakers. A list of requests for each icebreaker is maintained and updated as the vessel moves from one zone to another. The vessel is removed from all lists once it reaches a port [20].

The model can change the directed pathways during the model run, which allows for adjusting the shipping routes for more favorable ice conditions. Respectively, there is a need for an algorithm for transition between the directed pathways. The ongoing journeys are completed on the old directed pathways, and the new journeys are scheduled on the new directed pathways [20]. Icebreakers need to coordinate between both sets of directed pathways until all traffic flows smoothly on new directed pathways. Lu et al. [16] applied the model to a new region – the Gulf of Finland and the Gulf of Riga – considering Estonian and Finnish traffic and a new set of icebreakers. This did not require modifying the core modules of the model and demonstrated its significant flexibility.

### 2.3 *Key performance indicators for assessing the efficiency of the winter navigation system*

The assessment criterion has a critical role in estimating the efficiency of the winter navigation system. The winter navigation system is a complex entity with many qualities. Most of them are naturally contradicting, resulting in the need to find a trade-off between different KPIs. Kulkarni et al. [4] proposed measuring the efficiency of the FSWNS using the total waiting time (TWT) of merchant ships for icebreaking assistance as per (1). The total waiting time is often used in the FSWNS shipping practice.

$$TWT = \sum_{n_v=1}^{n_{v,max}} \sum_{0}^{T} W_{n_v} \quad (1)$$

where $n_v$ is the number of a simulated merchant ship, $T$ is the simulation time (days), $W_{nv}$ is the accumulated waiting time of the vessel number $n_v$ in minutes.

The total waiting time is the most straightforward KPI. Advancing the framework [4], Kondratenko et al. [15] demonstrated that although the total waiting time is an important KPI, it may prioritize less sustainable solutions. Minimizing the total waiting time of the WNS corresponds to more intensive use of the resources, e.g., leads to faster speeds of merchant ships and icebreakers with a higher total running time of the icebreakers, resulting in increased fuel consumption. Kondratenko et al. [15] proposed using the total CO2 emissions (2) and the total cost of the WNS operation (3) as additional KPIs for more sustainable and informed decision-making. The total CO2 emissions ($E_{CO2}$) and cost are estimated for all merchant ships and icebreakers.

$$E_{CO_2} = \sum_{n=1}^{n_{max}} \sum_{t=1}^{t_{max}} \Delta t' C_f \left( \frac{P_d SFC_1}{\eta_{tr}} + \frac{P_{hl} SFC_2}{\eta_{hl}} \right) \quad (2)$$

where $n$ is the number of simulated vessels, including icebreakers, $t$ is the number of the simulation period, and $\Delta t'$ is the duration of the simulation period. The simulation period ends if external circumstances affect the speed or the propulsion power in use $P_d$ (kW). $C_f$ is the conversion factor between fuel consumption and $CO_2$ emissions [21-26]. $P_{hl}$ is the hotel load – the power required for non-propulsion power consumers of a ship, estimated as a function of vessel type, size, and capacity using the statistical method by the Central Marine Research & Design Institute [27]. $SFC_1$ and $SFC_2$ are the specific fuel consumptions (t/kWh) for the main engine and the electric generator. The specific fuel consumption is calculated using quadratic polynomial approximations [15] depending on the engine load in % of the total maximum continuous rating (MCR). Approximations are provided for low-speed engines and medium-speed engines. $\eta_{tr}$ and $\eta_{hl}$ are the power transmission efficiencies for propulsion and the hotel load.

$$Cost = \sum_{n=1}^{n_{max}} \sum_{t=1}^{t_{max}} \Delta t' \left( R_n + C_{fuel} \left( \frac{P_d SFC_1}{\eta_{tr}} + \frac{P_{hl} SFC_2}{\eta_{hl}} \right) \right) \quad (3)$$

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

Using several discussed KPIs together results in a more systemic overview of the WNS system efficiency. Kondratenko et al. [15] demonstrated that their approach may provide the WNS with about a 7% decarbonizing effect or up to 14.2% cost reduction, depending on the priorities. They also show that the hotel loads are responsible for from 13.4% (moving at the max speed) to 100% (waiting for icebreaker assistance) of $CO_2$ emissions of a merchant ship on different modes of operation, and correspondingly must be considered in sustainable decision-making.

## 3 STUDYING NEW OPPORTUNITIES TO ENHANCE THE EFFICIENCY OF WINTER NAVIGATION SYSTEMS

Lu et al. [16] demonstrated that different ice conditions associated with different winters significantly affect the total waiting time, the need for icebreakers, and $CO_2$ emissions. Lu et al. [16] and Kondratenko et al. [15] also concluded that providing a more capable icebreaker fleet (in terms of their number and ice class) with fixed ice conditions improves the efficiency of the WNS till a specific point when further strengthening of the icebreaking fleet results in high additional cost with insignificant effect.

The present study provides further analysis of how the icebreaker assistance parameters and ice conditions affect the efficiency of the FSWNS. In the original approach by Kulkarni et al. [4], all the modeled icebreakers are available for the entire simulation time. However, in the shipping practice, the number of icebreakers is adjusted considering the dynamics of ice conditions, starting from a few icebreakers in the early winter and gradually adding more icebreakers later. In the present research, we implement the algorithm to account for the dynamics of the icebreaker resource availability and provide the corresponding simulation experiments. We also study the influence of the icebreaker allocation in different icebreaking zones on the efficiency of the FSWNS. Finally, we analyze how the location of the directed pathways influences the WNS efficiency and provide insights into the importance of ice routing of ships in the FSWNS.

### 3.1 *Preparing new algorithms and input data for modeling more WNS features*

The new features to be modeled are dynamics of the icebreaker availability, optimization of icebreaker allocation, and dynamics of the directed pathways. The basic scenario (Scenario 1) is discussed with the Finnish Transport Infrastructure Agency specialists and represents the existing practice. The selected AIS traffic data corresponds to one month of winter 2018 (15 Jan – 15 Feb) – an average winter from traffic and ice perspectives. The AIS data includes 485 voyages of 181 merchant vessels. Icebreaker data is provided in Table I, where all icebreakers have medium-speed engines. Fig. 7 shows on the map the icebreaking assistance zones applied in the simulation, and Fig. 8 shows the relevant zones for icebreakers and their operating schedule. According to the schedule, the number of operating icebreakers grows from four at the beginning of the simulation to nine at the end. Technically, this is achieved by blocking the ability of a merchant ship to select the icebreaker for assistance before its starting date of operation.

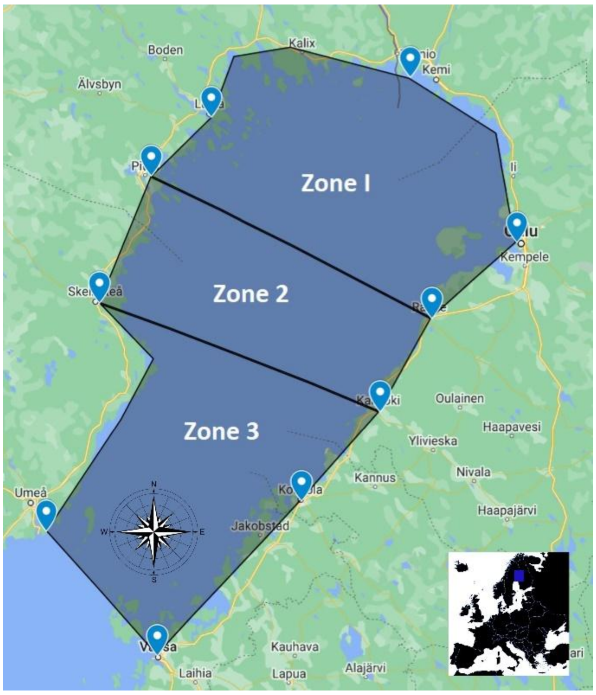


Figure 7. Icebreaking assistance zones in the Bay of Bothnia assumed in the simulation.

Table 1. Parameters of the icebreakers for the case study, where home port identification numbers are as follows: 25 is Quarken, 3 is Oulu, and 56 is Lulea.

| Name | Type | Home port | Engine power, kW | Propulsion, kW | Transmission | Engine | SFC (100% power), g/kWh |
|---|---|---|---|---|---|---|---|
| Polaris | A | 25 | 21000 | 19000 | Diesel-electric | Medium-speed | 185 |
| Otso | A | 3 | 21840 | 15000 | Diesel-electric | Medium-speed | 185 |
| Kontio | A | 3 | 21840 | 15000 | Diesel-electric | Medium-speed | 185 |
| Urho | B | 25 | 17100 | 16200 | Diesel-electric | Medium-speed | 175 |
| Frej | B | 56 | 17100 | 16200 | Diesel-electric | Medium-speed | 175 |
| Oden | A | 56 | 18000 | 18000 | Shaft | Medium-speed | 185 |
| Ymer | B | 56 | 17100 | 16200 | Diesel-electric | Medium-speed | 175 |
| Thetis | C | 56 | 3500 | 3500 | Shaft | Medium-speed | 180 |
| Ale | C | 56 | 3500 | 3500 | Shaft | Medium-speed | 180 |

In the original model by Kulkarni et al. [4], the maximum number of icebreakers per zone is assumed to be two. The ID number of the last used icebreaker in a specific zone is stored in a variable, and the vessel selects another icebreaker to assist vessels in this zone. According to the icebreaker schedule assumed in the present study (see Fig. 8), the available icebreaker resources are dynamic, and the maximum number of icebreakers per zone is up to four. This is achieved through the vessel selecting the icebreaker (see Fig. 9) according to the uniform distribution by drawing the random number from 0 to the maximum number of icebreakers in the zone. The random number is drawn again if the number belongs to an icebreaker whose schedule has not started.

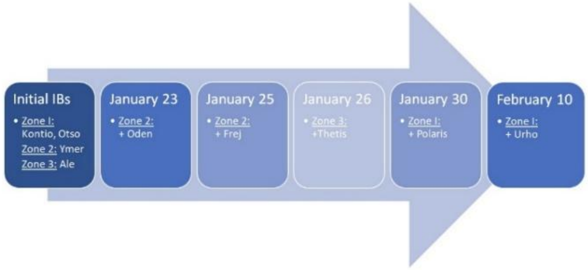


Figure 8. Operation schedule for icebreakers in the Bay of Bothnia with the starting dates.

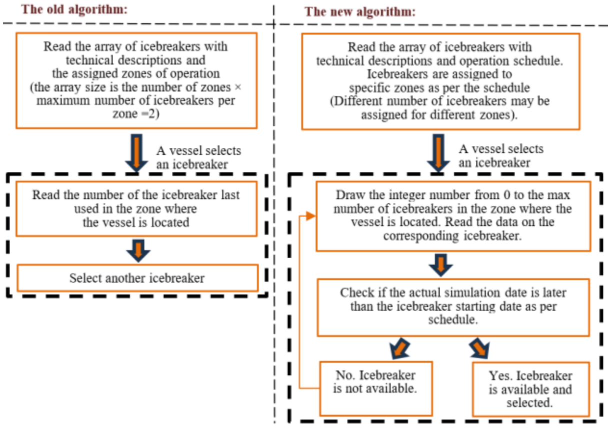


Figure 9. The algorithm for a vessel to select an icebreaker for assistance during the simulation.

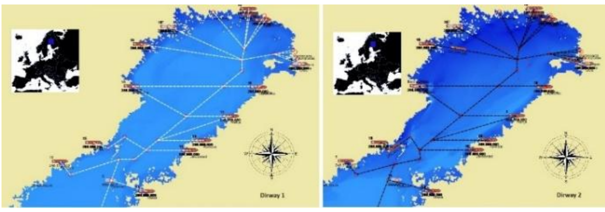

Figure 10. The directed pathways in the Bay of Bothnia for the considered case studies.

We consider two options for directed pathways (see Figure 10) to study the effect of their change on the WNS efficiency. Directed pathway (Dirway) 1 is closer to the Eastern coast of the Bay of Bothnia, and Dirway 2 is near its center. Because of spatial ice variation, ice conditions are different for different directed pathways. This allows us to analyze the importance of providing accurate recommendations on directed pathways, i.e., whether it is worth carefully selecting the most beneficial directed pathways or whether it could be deemed insignificant for the chosen type of winter. In the case studies, we considered three different options for using directed pathways: vessels moving along Dirway 1, Dirway 2, and stochastically migrating between them. For example, in the basic scenario (Scenario 1), directed pathways are randomly changed one time per day.

The case studies include seven different scenarios (see Table II). Considering that the model is stochastic, several simulation rounds were performed for every scenario, resulting in 36 simulation runs in total, with an accumulated simulation time of about 21 hours for the average office laptop. The simulation assumes that the icebreaking assistance threshold is 5 knots and that every merchant vessel is assisted individually.

### 3.2 *Simulation results for the case studies*

Simulation results for different scenarios are presented in Table III and Figure 11. Most simulations (16 rounds) are performed for the basic Scenario 1. It is noted that the number of simulation rounds is different for some scenarios, which may cause a selection bias of unequally represented statistics. Figure 11 shows significant variations in KPIs for Scenario 1, e.g., about a 45% difference in the total waiting time and a 7.5% difference in CO2 emissions. This difference is caused by the stochasticity associated with the icebreaking decision-making and changes of the directed pathways. Finding the reasons behind those fluctuations may unlock significant potential for optimization of the FSWNS. Scenario 2 differs from Scenario 1 by deterministic directed pathways: the vessels navigate using only Dirway 1. Variations for Scenario 2 (5 rounds) account for about a 24% difference in the total waiting time and a 3.7% difference in CO2 emissions. The average CO2 emissions for Scenario 2 are only about 1% lower than for Scenario 1, but the corresponding average total waiting time is almost 17% higher. This means that for the considered conditions, ice routing of ships (i.e., the directed pathways optimization) may be beneficial to significantly reduce the total waiting time of the FSWNS if the icebreaker resource is limited (e.g., by the limited number of available icebreakers and their schedule) and their location is not optimized.

Scenario 3 (3 rounds) is compared with Scenario 1 to analyze how the availability of all icebreakers during the simulation period affects the KPIs. The results show that the difference in KPIs is insignificant, which means that the schedule (see Figure 8) proposed by the Finnish Transport Infrastructure Agency experts is nearly optimal for the proposed allocation of the icebreakers.

Table 2. Values of the WNS parameters in the case studies. Icebreakers are abbreviated as IB.

| Case | Dirway | Schedule | IB Location |
|---|---|---|---|
| Scenario 1 | Stochastic | Dynamic | Basic |
| Scenario 2 | Dirway 1 | Dynamic | Basic |
| Scenario 3 | Stochastic | All IB available | Basic |
| Scenario 4 | Stochastic | Dynamic | Optimized |
| Scenario 5 | Stochastic | All IB available | Optimized |
| Scenario 6 | Dirway 1 | All IB available | Optimized |
| Scenario 7 | Dirway 2 | All IB available | Optimized |

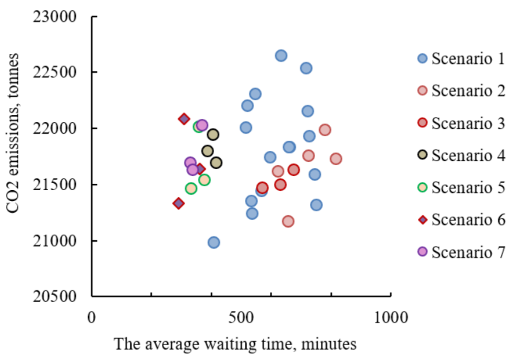


Figure 11. The values of KPIs for different scenarios of the case study.

Simulations for Scenarios 1 – 3 showed that they have shared problems – starting from the beginning of February, many ships are stuck in Zone 3, but Zones 1 and 2 are free from the ship traffic (see Figure 12). This problem can be mitigated by optimizing the allocation of the icebreakers (Scenario 4), using the rest of the parameters as in Scenario 1. Figure 13 shows the improved schedule, where the icebreakers are redistributed to provide more assistance in Zone 3, and their operation time is kept unchanged.

The simulation results for Scenario 4 (see Figure 11 and Table III) demonstrate a 35% reduction in the average total waiting time of the FSWNS compared to Scenario 1, when the average CO2 emissions stay almost the same. This means that optimized allocation of icebreakers without changing their operation time may be a very efficient method to improve the performance and cost-efficiency of the FSWNS.

Previously, Scenario 3 demonstrated that the availability of icebreakers during the entire simulation period insignificantly affects the KPIs for the basic allocation of the icebreakers. Scenario 5 is designed to check if this conclusion is still relevant for their optimized allocation. The corresponding simulation results demonstrate a 42% average reduction in the total waiting time of the FSWNS and the same CO2 emissions compared to Scenario 1. This demonstrates an additional 7% reduction in the total waiting time of the FSWNS compared to Scenario 4 due to extended icebreaker re-sources assuming the optimized allocation of icebreakers. Figure 14 shows that unlike Scenario 3 (Figure 12), the vessels are evenly distributed between the icebreaker assistance zones for the same virtual date, resulting in enhanced performance of the FSWNS, especially at the final stages of the simulation when the ice is the thickest. Scenarios 6 and 7 show that using deterministic directed pathways may result in about a 6% additional reduction of the total waiting time, associated with no need for transition between the directed pathways.

Table 3. Simulation results for different scenarios.

| Number of the round | The average waiting time, minutes | The total fuel consumption, tonnes | CO2 emissions, tonnes |
|---|---|---|---|
| | Scenario 1 | | |
| 1 | 746 | 6853 | 21587 |
| 2 | 633 | 7191 | 22652 |
| 3 | 517 | 6987 | 22009 |
| 4 | 728 | 6962 | 21930 |
| 5 | 409 | 6662 | 20985 |
| 6 | 662 | 6932 | 21836 |
| 7 | 661 | 6932 | 21836 |
| 8 | 547 | 7081 | 22305 |
| 9 | 538 | 6743 | 21240 |
| 10 | 521 | 7049 | 22204 |
| 11 | 751 | 6767 | 21316 |
| 12 | 718 | 7154 | 22535 |
| 13 | 723 | 7033 | 22154 |
| 14 | 596 | 6902 | 21741 |
| 15 | 567 | 6808 | 21445 |
| 16 | 535 | 6778 | 21351 |
| | Scenario 2 | | |
| 1 | 622 | 6862 | 21615 |
| 2 | 656 | 6720 | 21168 |
| 3 | 816 | 6897 | 21726 |
| 4 | 779 | 6981 | 21990 |
| 5 | 726 | 6906 | 21754 |
| | Scenario 3 | | |
| 1 | 676 | 6866 | 21628 |
| 2 | 570 | 6816 | 21470 |
| 3 | 630 | 6825 | 21499 |

| | | | |
|---|---|---|---|
| Scenario 4 | | | |
| 1 | 415 | 6886 | 21691 |
| 2 | 388 | 6921 | 21801 |
| 3 | 405 | 6966 | 21943 |
| Scenario 5 | | | |
| 1 | 359 | 6988 | 22012 |
| 2 | 333 | 6815 | 21467 |
| 3 | 377 | 6839 | 21543 |
| Scenario 6 | | | |
| 1 | 291 | 6772 | 21332 |
| 2 | 309 | 7012 | 22088 |
| 3 | 362 | 6870 | 21641 |
| Scenario 7 | | | |
| 1 | 331 | 6886 | 21691 |
| 2 | 338 | 6866 | 21628 |
| 3 | 370 | 6993 | 22028 |

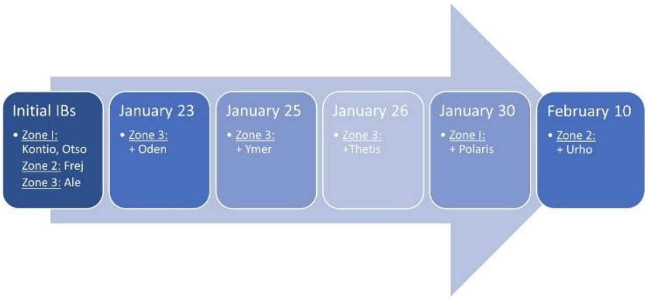


Figure 13. Optimized operation schedule for icebreakers in the Bay of Bothnia. The icebreakers are redistributed to provide more assistance in Zone 3.

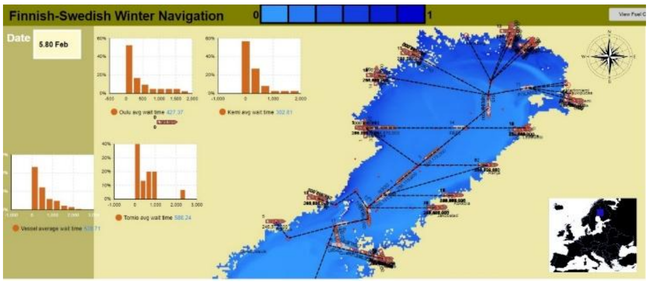


Figure 14. Scenario 5, awaiting vessels are equally distributed per zones.

## 4 DISCUSSION

The developed simulation tool aims to capture all the main elements of the winter navigation system: ice-going ships, icebreakers, varying ice conditions, and varying situations for independent navigation and assisting ships in ice. These elements are challenging to simulate. Firstly, the ice-going performance of vessels and icebreakers depends on many specific technical parameters of a ship and may vary for different ice conditions. For example, an icebreaker designed for navigation in a lake may not necessarily show the best performance for navigation in sea ice. Secondly, modeling ice conditions is challenging. Ice is very dynamic – it changes fast, even for one day. Moreover, it is usually necessary to reflect all the complexities of ice conditions and reliably simulate the average speed of a ship using only one value of the equivalent ice thickness. That is why the evaluation of the equivalent ice thickness needs accurate physics-based models to simulate the ship performance in varying ice conditions.

A critical aspect of the WNS simulation studied in the present research is how to model the decision-making process of icebreaker captains coordinating all maritime operations during wintertime. This has a significant effect on the efficiency of the winter navigation system. This decision-making process should include knowledge of the allocation of icebreakers in the studied region and how their availability changes in time, a summary of the ships being in or approaching the studied area and their ice-going performance, recommended routes for ships to follow and receive icebreaker assistance, and the most probable development of ice conditions in the near future.

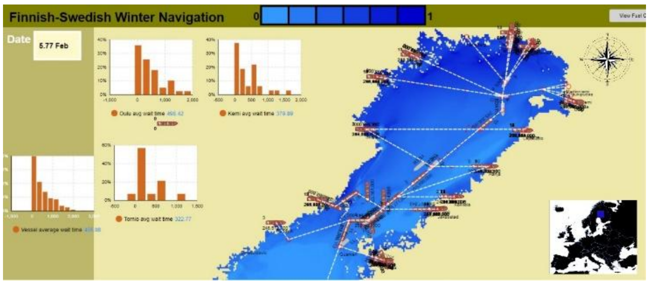


Figure 12. Scenario 3, vessels are congested in Zone 3, but Zones 1 and 2 are free from the ship traffic.

The newly developed functionality allowed us to analyze how some of these parameters affect the WNS performance. We studied the isolated and combined influence of changing the dynamics of the icebreaker resource availability, optimizing ice-breaker allocation in the Bay of Bothnia, and varying the directed pathways on the WNS efficiency. The results of the case studies revealed the complex, non-trivial effects of the studied factors, especially when different measures are applied simultaneously. We conclude that the total waiting time is susceptible to the examined factors and recommend considering them if the total waiting time is essential for decision-making. However, unlike some WNS parameters considered in the study by Kondratenko et al. [15], the examined factors affect $CO_2$ emissions insignificantly under the studied conditions and assumptions.

The calculations indicated that optimizing icebreaker allocation in the Bay of Bothnia is the most effective isolated measure to reduce the total waiting time by up to 35%. Based on the case studies, we concluded that solely extending the availability of all icebreakers for the entire simulation period does not improve the performance of the WNS. The latter, however, may indicate that the icebreaker availability schedule used in the basic scenario is already near-optimal for the basic allocation of the icebreakers. Complementing the optimized icebreaker allocation with the extended availability of the icebreakers provides an additional 7% reduction in the total waiting time, resulting in a 42% reduction compared to the basic scenario. Further enhancing the WNS through the improved directed pathways gives 6% less total waiting time, resulting in a 48% total reduction compared to the basic scenario.

The case studies, therefore, demonstrate that more intelligent usage of the existing resources (through optimizing icebreaker allocation and directed pathways) may be much more efficient than the expensive usage of more resources (through the charter of icebreakers for a more extended period). We may conclude that the development of the WNS simulation tools has significant prospects for uncovering the full potential of the ice-going fleet.

The demonstrated simulation tool has the following limitations. Firstly, in the present form, the tool mainly uses the maximum waiting time for ice-going ships as the main decision-making criteria, which is naturally too simple. Secondly, the methods used to evaluate the equivalent ice thickness for these ice conditions need further re-search on how to link the equivalent ice thickness calculation methods to the main particulars of the ice-going ships so that the performance-equivalence, rather than volume-equivalence, ice thickness can be achieved. Historically, ship performance in level ice has been the dominating research area for developing analytical formulations for ship resistance. The other ice conditions, such as ridges, dynamic moving ice, and ice floes with varying concentrations, have obtained less attention. Although some randomness has been included in this paper, significant uncertainties are still associated with information about ice conditions and ship performance evaluation. Quantification of such uncertainties can be an important direction for future work.

However, the results of applying the system-level simulation tool are promising despite the existing challenges. This is a unique tool worldwide simulating all the main elements of the winter navigation system.

## 5 CONCLUSIONS

The ice presence complicates maritime navigation in northern regions, which requires better ice-going qualities of ships and icebreaking assistance. Developing a simulation tool to study the performance of winter navigation activities in the Baltic Sea region at the maritime system level may significantly improve the quality of decision-making, resulting in more efficient and sustainable shipping. In the present paper, we demonstrated newly developed algorithms and case studies for the simulation of the Finnish-Swedish Winter Navigation System to predict the need for icebreakers and to plan their operation policies in the future. Specifically, extending the methods [4] and [15] with the newly developed functionality allowed us to analyze the influence of changing the dynamics of the icebreaker resource availability, optimizing ice-breaker allocation in the Bay of Bothnia, and varying the directed pathways on the WNS efficiency. The results of the case studies demonstrated that the total waiting time is significantly sensitive to the studied factors.

We concluded that optimizing icebreaker allocation in the Bay of Bothnia is the most effective isolated measure to reduce the total waiting time and that solely extending the availability of all icebreakers for the entire simulation period is not always effective. Complementing the optimized icebreaker allocation with the extended availability of the icebreakers and the improved directed pathways may result in a 48% total re-duction of the total waiting time compared to the basic scenario. The case studies demonstrated that more intelligent usage of the existing icebreaker resources may be much more efficient than the expensive usage of more resources.

The tool has significant potential to provide recommendations to reduce the total waiting time of the transport ships for icebreaking assistance. However, it is necessary to advance the methodology for estimating the equivalent ice thickness [28-30] and calculating h-v curves for different ships and ice conditions for more reliable modeling of the ship performance in ice, e.g., by means of ice tank experiments [31-35].

## STATEMENTS AND DECLARATIONS

The paper reuses the vector map of Europe distributed under the Creative Commons Attribution-Share Alike 4.0 International license (https://commons.wikimedia.org/wiki/File:Blank_map_of_Europe_cropped_%28blue%29.svg). In addition, the authors would like to thank Aker Arctic Technology Inc for providing the sample ship database containing established h-v curves.

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