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System level simulation of the winter navigation in the Baltic Sea

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ABSTRACT

Efficient winter navigation has crucial importance for Finland as all Finnish harbors are icebound every winter. A winter navigation system level simulation tool has been developed to analyse the marine traffic in wintertime and to analyse the present and future need of icebreakers when both marine traffic patterns, ice-going ship characteristics and ice conditions will change. This paper summarises the basic principle of the tool and presents some recent applications together with the conducted verification and validation. The tool has been applied both in the northern part of the Baltic Sea and in the south to study the winter navigation system: on the Bay of Bothnia for Finnish marine traffic and the Gulf of Finland for Estonian marine traffic.

KEY WORDS

Maritime; Winter navigation; Simulation; System level; Icebreaking

INTRODUCTION

The Baltic Sea holds significant socio-economic importance for the surrounding nations such as Finland, Estonia, and Sweden. It serves as a vital transportation route for goods, services, and passengers, while also supporting essential ecological systems. Ensuring the reliability and efficiency of maritime operations in this region is crucial. Particularly challenging is the winter season, when substantial portions of the northern Baltic Sea are covered with ice, a phenomenon that varies greatly from year to year in terms of extent. In response to these challenges and to facilitate safe and efficient navigation throughout the year, the Finnish-Swedish Winter Navigation System (FSWNS) has been implemented (Kulkarni et al., 2022, Trafi 2022).

Finland has more than 150 years' experience of winter navigation. The FSWNS system has been developed to guarantee safe and reliable shipping throughout the winter even though many of the Finnish harbours are ice-covered each winter. The system consists of three elements: ice-strengthened ships, icebreaker assistance, and traffic restrictions. The traffic restrictions ensure that only ships with some minimum size and ice class will get icebreaker assistance on the winter period and the harder the ice conditions the stricter will be the traffic restrictions. This is to guarantee that the icebreaker fleet is capable of offering the service required to keep the winter navigation operations safe and aiming for minimum waiting time for the merchant vessels. In order to ensure ships possess the necessary ice-going capabilities for safe and efficient operations, adherence to the Finnish–Swedish Ice Class Rules (FSICR) is imperative. (Trafi, 2022).

We have developed during the last 10 years a simulation tool to study the system level performance of the winter navigations in Finland (Lindeberg et al., 2015, 2018, Kulkarni et al., 2022a, Kulkarni et al., 2022b). The main aim of the tool development

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has been to obtain a research-based prototype and decision-making aide that can be used to simulate the need of icebreakers as well as socio-economical and environmental impacts related to FSWNS in the future when both ice conditions, maritime traffic and characteristics of ice-strengthened ships will be under dynamic change. Climate change will affect the ice conditions so that the maximum ice thickness might decrease but the annual variations will be high and the ice movements can increase causing other type of challenges for the winter navigation system. Ship's size seems to increase and at the same time the new strict environment regulations will decrease the used engine power on ships. In efforts to curb Greenhouse Gas emissions from ships, the International Maritime Organization implemented the Energy Efficiency Design Index (EEDI) regulations in 2011 (EEDI, 2022). These regulations are geared towards promoting the adoption of highly energy-efficient solutions in maritime operations. While the focus is on reducing GHG emissions, the technical specifications of these regulations restrict the maximum propulsion power installed on ships and encourage the use of hull forms optimized for open water conditions. This will decrease dramatically the ice-going capabilities of these ships. All these aspects are included in the simulation tool.

The aim of this paper is to shortly describe the current status of the simulation tool. The main structure and elements of the tool will be described. In addition, some recent case studies with the tool will be summarized to demonstrate the extent of its application: a) Validation of the tool, b) Optimization of icebreaker assistance for sustainable shipping and c) Analysis of the icebreaker needs in Estonia.

DESCRIPTION OF THE TOOL

General description of the tool

The objective of the tool remains as described above: to simulate the FSWNS performance across a range of potential operating scenarios, aiding decision-making regarding its operation and development, including considerations like icebreaking resources and ice class regulations. To achieve this, the tool is designed to replicate winter traffic patterns under various operating conditions, incorporating elements such as icebreaker scheduling and directed pathway adjustments. Icebreaker scheduling involves determining the number of icebreakers available each day, their initial positions, and their designated operational areas. Additionally, mathematical modeling is employed at the ship level to capture individual vessel interactions with ice conditions and their impact on overall traffic flow. Vessel speeds under different ice conditions, such as convoys and towing, are calculated using closed-form expressions. The proposed tool enables users to assess how the FSWNS would perform under different hypothetical scenarios, enhancing understanding of the system's behavior. This project aims to combine the strengths of simulation modeling with the expertise of maritime professionals. Figure 1 illustrates a schematic block diagram of the simulation tool. (Kulkarni et al., 2022a)

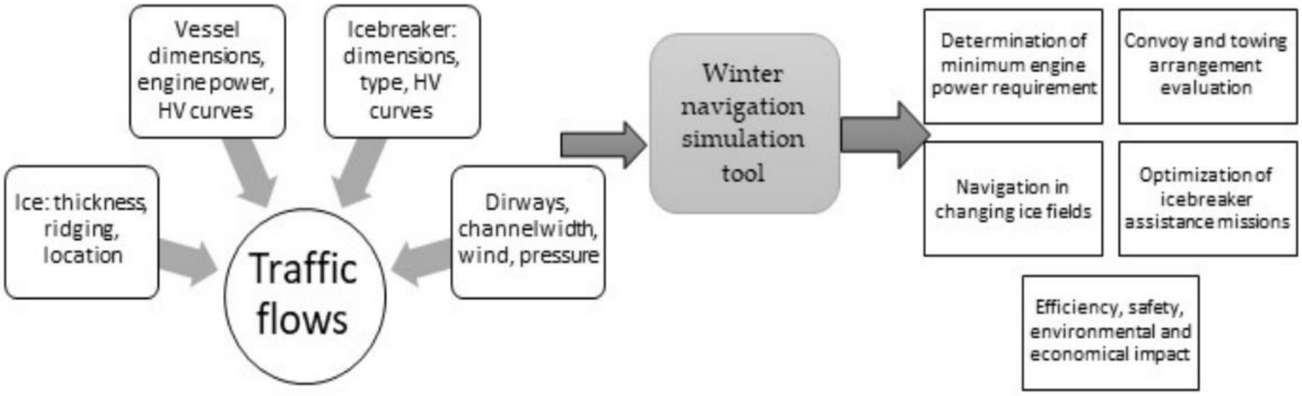


Figure 1: Simulation tool structure (Kulkarni et al., 2022a)

The simulation tool incorporates a hybrid approach, utilizing discrete-event and agent-based simulation techniques along with process flow modeling. This selection of modeling methodologies enables the visualization of simulation processes and outcomes, as well as the integration of stochastic elements. Individual components within the FSWNS, e.g., merchant ships, icebreakers, and ports, are represented using an agent-based framework, which includes detailed decision-making processes. Each component, whether a merchant ships or icebreaker, faces numerous decisions throughout the winter season, responding to changing situations. The decision process for each component is governed by a series of rules presented in an if-then-else format, dictating adjustments to direction, speed, and operational mode according to system parameters. Moreover, an optimization logic is employed for icebreakers to determine the most effective ways for assisting vessels. (Kulkarni et al, 2022a).

The tool is designed to be utilized by domain experts, serving as a complement to their expertise rather than functioning as a standalone solution. Experts provide crucial details regarding resource availability (such as the available icebreakers and operational ports on a specific day) and other scenario specifics not available from existing data sources. The model inputs encompass vessel particulars, including dimensions of ships and coefficients of hv curve (abbreviation for the ice thickness vs ship's speed), traffic patterns, and ice conditions. The inputs are processed to derive formula for vessel and icebreaker speed variations, trip parameters (origin, destination, departure time), daily ice conditions, and dirway locations (dirway defines the ship path through ice). Traffic data are obtained through the processing of AIS (Automatic Identification System) data, which serves as essential input to the simulation model. At its core, the simulation engine incorporates agent-based models to replicate entity behaviors, discrete-event models to emulate both scheduled and random occurrences, and process flow models to depict the movements of vessels and icebreakers at sea and within ports. It also includes visualization functionalities, such as a color-coded scheme that illustrates different ice thicknesses, with darker hues of blue representing thicker ice layers. The primary simulation output is a visualization of traffic flows illustrating vessel movements across evolving dirways towards destinations see Figure 2. Vessel speeds adjust according to ice conditions along their routes, while icebreakers are observed assisting vessels unable to maintain speeds above a specified threshold. Following the simulation's completion, a Key Performance Index (KPI) referred to as the average waiting time is generated. These results are then presented to the domain expert, who serves as the decision-maker, for potential adjustments to future configurations. Subsequently, the expert offers feedback to enhance the simulation tool iteratively. (Kulkarni et al., 2022a).

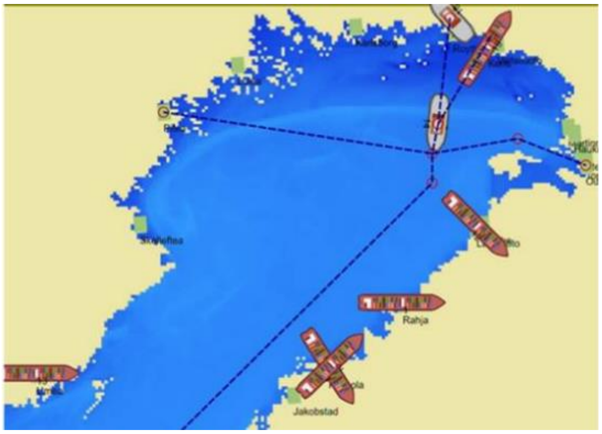


Figure 2: Visualization of ice fields, dirways and ships on the Bay of Bothnia (Kulkarni et al., 2022a)

Definition of ice conditions

To accurately depict the complexities of winter navigation, it is crucial to include ice conditions with precision. Ice data encompasses various aspects like thickness, concentration, and topography, typically sourced from Finnish Meteorological Institute (FMI) ice charts. However, this data originates from diverse sources, necessitating the integration of multiple file formats to compile a comprehensive view of ice conditions. Furthermore, ice data is dynamic, with updates available hourly for each geographical grid. To facilitate integration into the model, this information undergoes suitable aggregation to balance detail with computational efficiency.

In the simulation, vessels must be responsive to these dynamic ice conditions, adjusting speeds or halting. This necessitates that vessels can continually understand ice information and adapt behavior throughout a journey. To achieve this, concepts like equivalent ice thickness and HV curves are employed. Equivalent ice thickness utilizes a mathematical formula to derive a single value representing ice thickness, incorporating factors such as concentration, thickness, and topography. This approach enables vessels in the simulation to effectively gauge and respond to changing ice conditions as they navigate. The formula given by Lindeberg et al. (2018) is used in the model for obtaining the equivalent ice thickness (Kulkarni et al., 2022a).

Given that ice conditions can vary daily, they can significantly impact routing decisions. Actual ice data is employed to compute the equivalent ice thickness, which is derived from averaging the ice volume within a grid. These ice data sets are updated on a daily basis, but the frequency of updates can be adjusted as needed. The equivalent ice thickness definition may vary depending on the available ice data. In this study, equivalent ice thickness is calculated as the product of concentration and thickness to maintain volume equivalence based on NetCDF data (Milakovic et al., 2020). The equations are similar to those used in Lindberg et al. (2018). For more information, readers are pointed to Sormunen et al. (2018).

Evaluation of ship performance in ice

The vessels simulated in the model must be responsive to fluctuations in ice conditions, adjusting their speeds accordingly or even halting when necessary. Each vessel is assigned an hv curve profile tailored to its dimensions, with Aker Arctic having developed numerous such curves for typical ice-capable ships as part of project Winmos I/Winmos II (2021). These hv curves are incorporated into the model as entity attributes, governing speed adjustments based on equivalent ice thickness. Each vessel is assigned an hv curve code. This code allows the vessel to reference the pertinent hv curve information during simulation runs. The expressions in level ice (v_l) and in the convoy (travel at a distance following an icebreaker) condition (v_d) to obtain ship speeds are provided in equations (1) and (2):

$$v_l = a_l h^3 + b_l h^2 + c_l h + v_{ow} \tag{1}$$

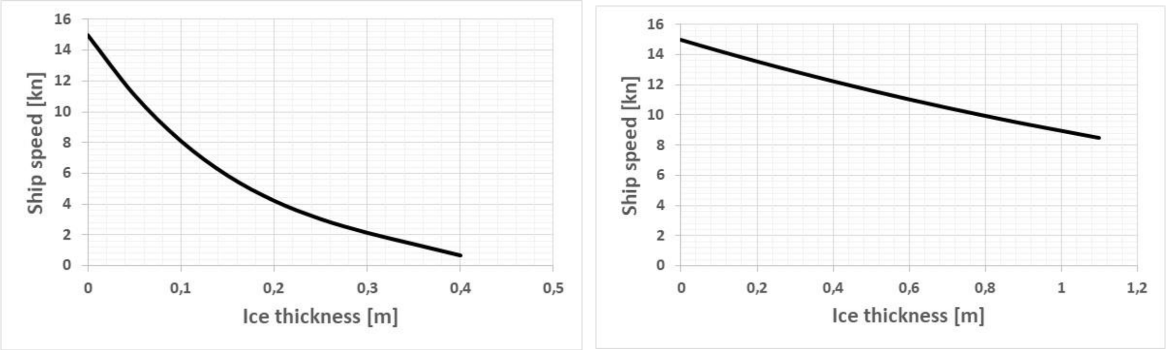
$$v_d = a_d h^3 + b_d h^2 + c_d h + v_{ow} \tag{2}$$

In the given equations, the symbol h represents the equivalent ice thickness, while the coefficients a, b, and c denote the parameters defining the relevant ship speed in the ice condition, and w signifies the speed in open water. Table 1 illustrates a standard array of coefficients for an hv curve.

Table 1: Example of hv curve coefficients

Hv_Ship	v_{ow} [kn]	a_l	b_l	c_l	a_d	b_d	c_d
Example	15	-199.84	210.24	-87.997	-0.1658	1.5976	-7.4582

The polynomial expressions of two representative hv curves are depicted in Figure 3. It is notable from both plots that the open water speed is maintained at 15 kn. In Figure 3A, it is evident that the speed decreases swiftly with escalating ice thickness, approaching nearly 0 kn at approximately 0.4 m. Conversely, Figure 3B illustrates that speeds can be sustained up to 9 kn for ice thicknesses ranging from 0.4 m to 1 m when in convoy.



A B

Figure 3: Example of h-v curves. (A) Vessel in level ice; (B) Vessel in convoy. (Kulkarni et al., 2022a)

The equivalent level ice thickness approach is used to make the simulation tool development systematic and easy to adapt. However, determination of equivalent level ice thickness is not straight forward process as various ice conditions require totally different approaches, as reviewed by Milakovi'c et al., (2020). For ridged ice, one approach used is to estimate the relative increase of level ice thickness based on the density of the ridges. The values used in the model are as follows: rafted ice + 7.5%, slightly ridged ice + 22.5%, ridged ice + 60%, and heavily ridged ice + 105% increase (Lindeberg et al., 2018). For floe ice with varying concentration no good methods exist so far to determine the equivalent level ice thickness.

In Aalto University, the latest development has been related to the topic: how to evaluate the ship resistance and hv curves on two different important cases: 1) The effect of vessel breadth on the resistance during escort and 2) The effect of closing channel and compressive ice on the resistance. Li et al. (2021) conducted thorough investigations on the characteristics of the hv curves in what is termed a 'narrow ice channel.' In scenarios involving escort and convoy operations, an icebreaker creates a passageway while accompanying ships trail along this designated path. However, if the width of the assisted ship exceeds that of the channel formed by the icebreaker, the created pathway becomes insufficient for the assisted ship. Consequently, the assisted ship must independently break through some ice. This situation is denoted as navigation in a 'narrow ice channel.' To address this, a model-scale test was initially carried out, simulating a ship navigating through ice channels with varying widths and ice thicknesses. Subsequently, numerical simulations of the model test scenarios were executed using an in-house simulation program specifically designed for ship operations in icy conditions. The simulation accurately captured the primary aspects of changes in ship resistance relative to channel width, validating its efficacy as a simulation tool. Further numerical simulations were then conducted with various other ships to gain comprehensive insights into ship performance in narrow ice channels. Emphasis was placed on evaluating the impact of channel width on ships' encountered resistance and achievable speed in icy conditions. Figure 4 illustrates an example of the obtained curves, with the parameter γ representing the relative breadth of the channel compared to the ship breadth. For instance, γ=0.25 indicates that the channel width is 25% of the vessel breadth. When γ=0, the scenario corresponds to breaking level ice, and with γ=1.0, the ship navigates in a channel with a width equal to the ship's breadth. An illustrative example is the Agulhas II, a ship with ice class PC 5, constructed in RMC for South Africa to operate in Antarctica's icy conditions.

The other case stated above, i.e. the closing channel due to the moving ice, has been studied by Lu et al., (2023). The moving ice will close the channel in front of the ship causing increased resistance mainly due to increase of frictional forces at the straight midship part of the vessel. This will cause dramatic decrease of ship speed in ice, as shown in Figure 5. The curves represent various compressive ice conditions (different ice drift speeds). There are mainly three clusters. The first cluster follows the original level ice h-v trend. The second cluster is the ones drops quickest. The third is the ones between the two clusters. They show the transitions from no compression to compressive ice conditions, which can also be defined as ‘critical ice speed’. After the ‘critical ice speed’ curve, the ship will totally follow the compressive ice clusters. In the critical ice speed, h-v curve also demonstrate ‘up and down’ feature which is affected by relative relationship between the broken ice cusps and ship speed. The ice movement is caused by the high wind and therefore the wind speed and direction on the navigation area should also be known before this can be included in our simulation tool and that development is still on-going.

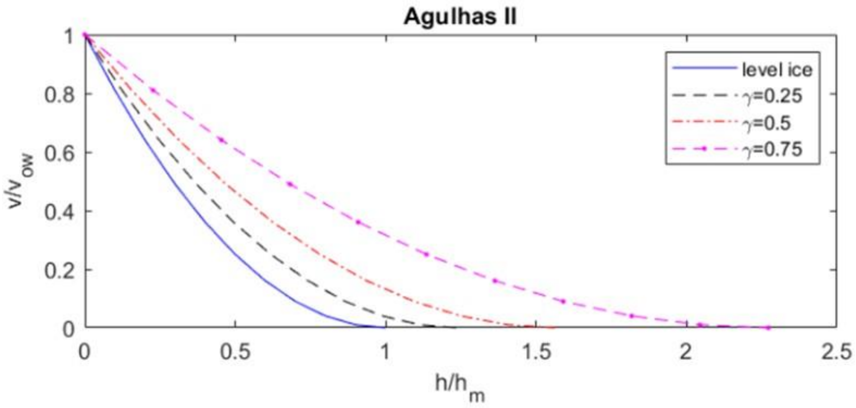


Figure 4: Example of h-v curves for narrow channel. Ice thickness is made non-dimensional by dividing it with the maximum level icebreaking capability of the ship and ship speed is relative to the open water speed. (Li et al. (2021)

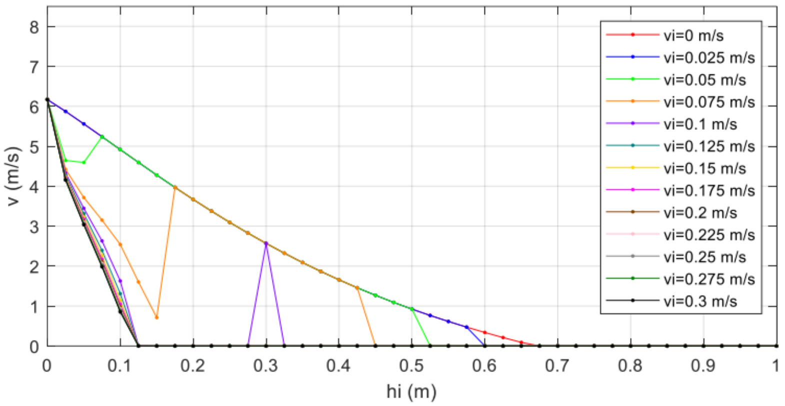


Figure 5: Example of h-v curves for closing channel for MS Envik. Ship initial speed is 5 kn and v_i is the speed on the ice movement transversal to the ship movement. (Lu et al. (2023)

Icebreaker decision making

The pathways navigated by vessels, termed dirways, constitute an integral part of the model. Dirways are established by icebreakers in ice-laden regions and are susceptible to alterations due to factors like wind, pressure, and evolving ice conditions. Another critical consideration involves the transition between dirways. As vessels traverse ongoing journeys on existing dirways, new journeys are concurrently scheduled on updated dirways. Icebreakers must effectively coordinate between the two sets of dirways until all traffic seamlessly transitions to the new routes. This dynamic process also impacts convoy formation and can influence system waiting times.

Vessel speeds fluctuate in alignment with their respective hv curves. If a vessel's speed falls below a predefined threshold, icebreaker assistance is solicited. Depending on the vessel's location, an appropriate icebreaker from the available fleet is selected. Convoys may form when multiple vessels require assistance in the same direction. The simulation concludes once all vessels have completed their scheduled journeys within the specified time frame. The operational area is divided into distinct operating zones, delineated based on prevailing ice conditions, which may evolve dynamically throughout the simulation. Each zone is ensured to have at least one icebreaker available. Icebreakers possess specific ice-going capabilities, modeled using hv curves akin to those employed for assisted ships (refer to Figure 3), with examples of icebreaker hv curves provided by Lindberg et al. (2018).

Despite being assigned specific zones, icebreakers frequently collaborate to make sure the safe and efficient operation of the entire system. Vessels often require assistance across different zones. Usually, one icebreaker leads a vessel through its designated operating zone, leaving the vessel at a secure stopping point known as a waypoint. The next icebreaker assumes responsibility for guiding the vessel further along its journey from there. However, icebreakers have the flexibility to operate beyond their designated zones to alleviate traffic congestion or assist larger vessels requiring dual icebreaker support. Icebreakers must dynamically make decisions regarding prioritizing vessel assistance, coordinating with other icebreakers, selecting paths, and organizing convoys. When a vessel becomes stopped in ice, it sends a distress signal to the icebreaker control unit, which may consist of an icebreaker with a coordinating captain or a decision-making unit on land. A free IB can also "predict that point. The different merchant vessel threshold speed to start the assistance is an input parameter in the tool. The responsible icebreaker calculates the vessel's potential route based on its current position and destination, identifying one or more icebreaker zones through which the vessel must navigate to reach its destination. A schedule is then devised for the vessel, updated each time it completes a zone. The initial icebreaker assigned to assist the vessel is dispatched to guide it to the end of its assigned zone or port if the port falls within the zone. At the conclusion of each zone, the vessel's route is reassessed as necessary, and the subsequent icebreaker is tasked with guiding it onward. A comprehensive list of requests for each icebreaker is maintained and updated as the vessel progresses from one zone to another. Once the vessel reaches a port, it is removed from all lists. This coordinated approach ensures the efficient movement of vessels through ice-covered waters. More detail description of the IB decision making can be found from Kulkarni et al. (2022a, 2022b).

VERIFICATION AND VALIDATION OF THE TOOL

To ensure the model reliability and instill confidence in its functionalities, both verification and validation processes are essential. Verification entails assessing whether the model behavior reflect the conceptual description and specifications. On the other hand, validation assesses the extent to which the modelling represent the real world from the perspective of end users. Essentially, verification addresses the question: " Is the model right?", while validation addresses the question: " Is this the right model?". Both processes can be conducted at both the individual ship level and the system level, as elaborated below.

Several challenges exist in the validation of this simulation tool. Firstly, despite the extensive AIS dataset, organizing and processing the data to suit the simulation is a complex task that demands dedicated attention. Secondly, the majority of data originate from a single common source, which was utilized to construct the model. Therefore, there are presently no additional data available solely for testing purposes. Thirdly, conducting trials of the tool alongside existing icebreaker management methods necessitates obtaining extensive permissions, undergoing checks, and adhering to regulations. Consequently, various validation approaches have been adopted for the simulation tool, detailed in the subsequent validation sections.

Verification

Field experts attended the demonstrations where the model was operated at a discernible pace. The KPIs included in this case are summarised next. They monitored vessel speeds across a localized area characterized by high ice variability to ensure their adaptation to changing ice conditions. Dirway alterations were also closely observed, with an expectation of changes occurring weekly throughout the runtime. Experts also examined waiting time averages at various ports and for all vessels collectively. Some of these experts had prior involvement in field assistance during the same timeframe. They corroborated that the Key

Performance Indicators (KPIs) obtained fell within acceptable ranges for the winter season, meaning less than 10% deviations. Moreover, the assistance numbers provided by each icebreaker was recorded and compared with reality (Kulkarni et al., 2022a).

Validation on a ship level

The validation on a ship level has been done by Sormunen et al. (2018). The main idea of the validation was to compare the speed variation on varying ice conditions for the Bay of Bothnia for one ice breaker and for the Gulf of Finland for one Ro-Ro vessel during winter 2010. The voyage length was few hours for both cases. The results indicate that the difference between AIS data and simulation model was less for the icebreaker (varying from -31 % to 41 %) than for the Ro-Ro (varying from -71 % to 61 %).

In a recent study by Kulkarni et al. (2024), a comprehensive approach to ship performance modeling is introduced, encompassing various parameters including ice conditions, power variations, and icebreaker assistance. This approach undergoes validation against real ship voyages. The h-v curves delineate the breaking capabilities of candidate ships against level ice, with the paper summarizing the methodologies employed for handling ice ridges, variable ice concentration, and ice floe sizes. Real-world ice fields often exhibit greater complexity than level ice, with variations in ice floe size and ice field concentration, as well as the formation of ice ridges under pressure. Equivalent ice thickness serves as a convenient means to streamline intricate ice fields into a single level-ice thickness, facilitating speed determination via the corresponding h-v curve. To validate the approach of ship performance modeling, real ship voyages documented by Kujala and Sundel (1991) are utilized as validation cases. These voyages were logged onboard corresponding ships during their visits to Finnish ports. Various parameters, like actual ship speed and power, are recorded, while ice parameters including level ice thickness, ice concentration, ridge sail height, and floe size are obtained by visual observation. Additionally, the operation modes (e.g., independent operation or assistance) are noted. This comprehensive dataset offers insights into the actual voyages, enabling ship speed estimations using the proposed approach, which can then be compared against the actual speeds observed during the voyages. In total, 12 ship voyages are included with 10 different vessels, with the typical duration of each voyage spanning a few hours. Comparing the average speed form the simulation tool and from the real observations, the relative difference is varying from – 47,5 % to + 7,2%.

Validation of the traffic system

For the traffic system in the simulation model, three different types of validations have been conducted:

1) Ship waiting times,
2) Ship arrival times,
3) Time used for each voyage.

These are described in future details next. Ship waiting time was validated by Lindberg et al. (2018) using the previous version of the tool, a deterministic simulation tool developed to analyze the performance of the FSWNS regarding the cumulative waiting time for icebreaker assistance under predefined operating conditions. Validation of the tool using real-world data suggests its reasonable accuracy. One month period from 15 January to 15 February on winter 2011 was used for the validation. A 1.7% margin was obtained to the average real life port waiting times based on AIS data.

Kulkarni et al. (2022a) validated the ship arrival times including winter traffic from 15 January 2018 to 15 February 2018 on the Bay of Bothnia. A total of 115 vessels were incorporated into the study, and a total of 249 trips were analyzed. Only level ice thickness was used to define the prevailing ice conditions for the used hv curves. These vessels were categorized into 18 vessel types with similar hv curves. The historical dataset comprises arrival and departure timestamps at various ports, along with the duration of stay at each port. Port departure times are integrated into the model as inputs. The arrival of a vessel at its designated destination port hinges on several factors, including ice conditions, dirways, icebreaker availability, and the prioritization logic employed by icebreakers when handling assistance requests from multiple vessels. One approach to validating the model involves comparing the scheduled arrival times of vessels at different ports with their historical counterparts. Typically, the arrival times were within few hours error margins but also few exceptional cases were found with the error of several days showing the sensitivity of system on a number of parameters, which require further analysis.

The latest validation was done by Winberg (2023) in his master’s thesis. Rather than validating for one winter, the model was studied on trip-level using three different historical winters, being 2011, 2018, and 2020 on the Bay of Bothnia. These represent the three different winter types of mild, average, and severe, classified by the Finnish Ice Service. One month period i.e. from mid-January to mid-February was used as the studied period. For the study, a trip-level validation is performed for the different winter classes (mild, average, severe). Trip-level validation is preferred, since that allows the individual trips to be studied, and thus help find the root cause for the errors more easily than using a broader system-level overview. Therefore, comparing the trip durations from real-life to the results provided by the simulation, are chosen as the main method of the validation. Winberg (2023) made detail study of the AIS data and filtered out a remarkable number of voyages due to the errors on the data and thereafter the data resulted in 232, 599 and 408 trips for the winters of 2011, 2018 and 2020, respectively. In the study, 45 reference vessel hv curves were used for the studied ships, and only level ice thickness was used to define the prevailing ice conditions for the used hv curves. Vessel speed threshold to start assistance was 3kn and convoy maximum speed 6 kn. The trip distance was from the Northern Quark strait to the harbour on the Bay of Bothnia, so typical voyage length is from few hours to few days. The average difference between the trip durations was 72.7 %, -90.1 % and 40.2 % for the winters of 2011, 2018 and 2020, respectively. This is naturally a remarkable scatter as the results obtained from the three winters are very diverse. Winberg (2023) summarises on his conclusions the following possible error sources:

- There is possibility of errors in the AIS data
- The waypoints used by vessels for navigation in the area do not correspond to the routes used in real-life
- Icebreaker decision making is not optimized and do not follow the real-life procedures
- Winds and currents impact on the ice movement are not included
- The optimized utilization of ice channels is not included
- Only one speed threshold for the icebreaker assistance is included
- Inaccuracies may be present on the used h-v curves

OPTIMIZATION OF ICEBREAKER ASSISTANCE FOR SUSTAINABLE SHIPPING

Kondratenko et al. (2023) employed the simulation tool to introduce a novel approach for decarbonizing shipping in icy conditions. This proposed method optimizes icebreaker support with a focus on both ecological and cost efficiency, thereby facilitating the implementation of more sustainable icebreaking strategies. While the fee of icebreaker assistance is not directly remitted to Finnish and Swedish organizations who provide such assistance, it is encompassed within the fairway fee collected by the government. This fee is contingent upon the ice class (only applicable to Finnish authorities) and the vessel size. As reported by Baltic Icebreaking Management (2020), the average total operational cost of one icebreaker during the 2019–2020 navigation season amounted to 4.91 million euros per month, with approximately 11 percent allocated to fuel expenses. The total amount of fuel needed by the assisted ships in ice is now known, but the simulation tool can be used to approximate this. The main research question is then what is the optimum number of icebreakers so that the total amount of fuel and emissions on the air can be minimized on the winter navigation system level. In other words, can we use some other KPIs as average waiting time in future, to account for both ecological and cost efficiency KPIs, supporting sustainable shipping in ice.

Kondratenko et al. (2023) expanded the model to incorporate an eco-efficiency Key Performance Indicator (KPI) by estimating the total CO2 emissions (in tons) of the FSWNS encompassing all transport vessels and icebreakers simulated in the analysis. While port emissions are negligible and remain unaffected by icebreaking assistance, they are thus not factored into the calculations. The total CO2 emissions are determined for the scheduled voyages of transport vessels and all simulated assistance operations conducted by the icebreakers. This can be done as the simulation tool knows the used engine power and voyage time and length for both icebreakers and assisted ships. Using standard approaches the fuel consumption as a function of engine power can be determined and conversion factor between fuel consumption and CO2 emission exists as well. The fuel cost can then also be determined once we know the total amount of fuel. The other economic costs in the model are included using the time charter rate (USD/hour) of a transport vessel or an icebreaker. More details of the approach used can be found from the paper by Kondratenko et al. (2023).

The case studies are established based on historical AIS traffic data and ice data during an average winter from traffic and ice perspective (15 Jan - 15 Feb 2018). Freight rates for each vessel are estimated based on publicly available data, taking into account the vessel's purpose and capacity (measured in deadweight (DW) or twenty-foot equivalent unit (TEU)). Estimated daily freight rates vary significantly, ranging from 4900 USD/day for small transport vessels to 43,000 USD/day for large vehicle carriers, and 60,000 USD/day for icebreakers. The study systematically varies the number and size of icebreakers, determining CO2 emissions and costs using the simulation tool. Findings indicate that current practices are close to optimal, but alternative operational strategies could potentially reduce greenhouse gas emissions by up to 7% or lower costs by up to 14.2%. Results suggest that the proposed approach holds promise in offering recommendations for environmental and economic policies aimed at decarbonizing Finnish-Swedish icebreaking assistance. Naturally, this is the first attempt to evaluate the other KPIs than average waiting time and the model needs improvements, but the study shows the strength of the tool to study also other KPIs.

ANALYSIS OF THE ICEBREAKER NEEDS IN ESTONIA

The latest application of the developed simulation tools has been the evaluation of icebreaker needs for Estonia until the year 2025 (Tapaninen at al., 2023). Figure 6 shows the developed model layout for Estonian maritime traffic. The main objective of the study was to simulate the Estonian wintertime traffic and analyse how many icebreakers Estonia will need as described next in further detail.

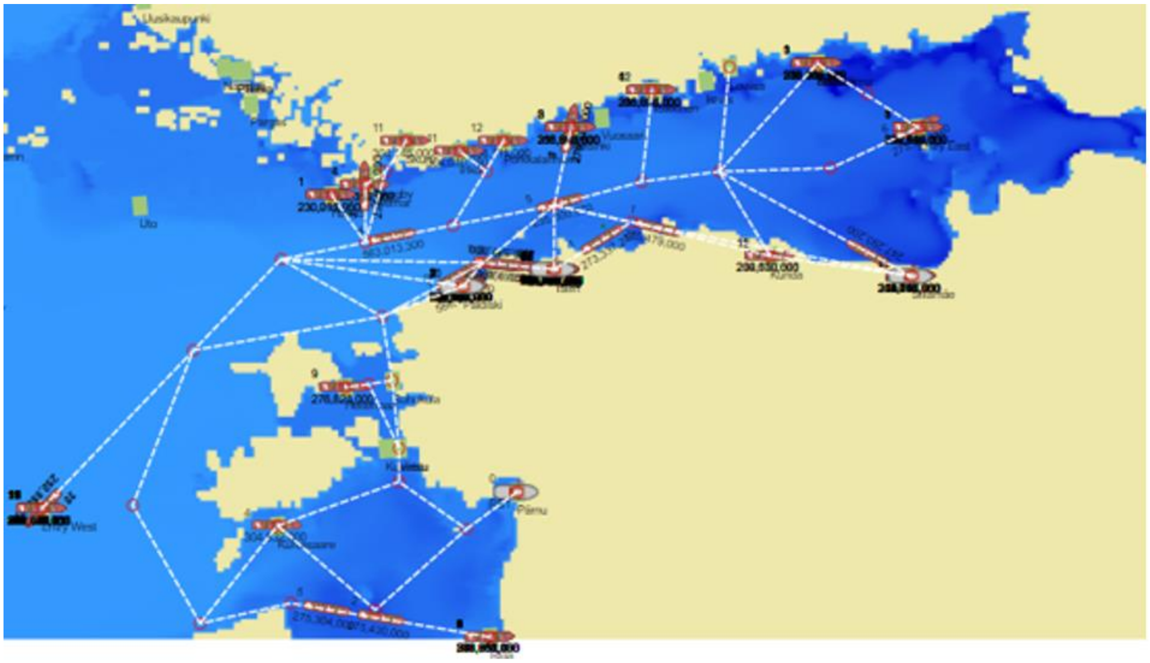


Figure 6: A demonstration of the Estonian Winter Navigation System model (Tapaninen et al., 2023)

Evaluation of ice conditions

The ice conditions on the Estonian water were analysed by Taltech, Department of Marine Systems. Figure 7 illustrates the mean and maximum ice thickness on Estonian waters based on the long-term data. As can be seen that there are winters with very minor amount of ice, but also hard winters with extensive ice coverage on Estonian harbours. Over the years 1993–2022 about 20% winters have been sever, 60% have been average, and 20% have been mild winters. As temperatures are projected to increase in climate scenarios, a rise in occurrence of average and mild winters is anticipated. Consequently, severe winters are expected to become significantly less frequent. Nevertheless, under extreme weather conditions in warmer climate scenarios, there remains a possibility for severe winters to occur. Consequently, the simulation tool was used to analyse the winter navigation system on a mild, average, and hard winter.

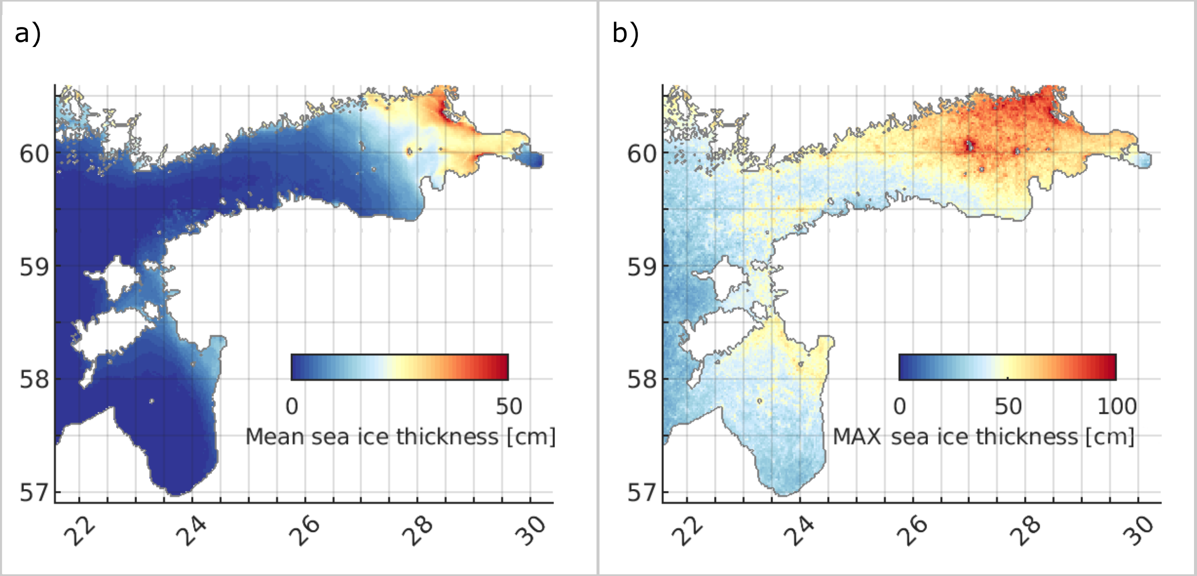


Figure 7: (a) Mean and (b) maximum of ice thickness. The values are retrieved from data between 1993 and 2021 (Tapaninen et al., 2023)

Simulated scenarios

In order to simulate the effects of the different combinations of icebreakers (IB), the scenarios given in Table 2 are used. Three of the used icebreakers are delegated to Gulf of Finland (GUF) and one to Gulf of Riga (GUR). IB scenario 1 includes two icebreakers, i.e. one in both areas and scenario 2 have three icebreakers, i.e. one in GUR and 2 in GUF, and scenario 3 activates all four icebreakers, i.e. one in GUR and 3 in GUF.

Table 2: Icebreaker scenarios studied (Tapaninen et al., 2023)

Icebreakers	Main Engine power [kW]	Shaft power [kW]	IB scenario 1	IB scenario 2	IB scenario 3
GUF, Primary IB	13000	10000	+	+	+
GUF, Secondary IB	9100	7000		+	+
GUF, Third IB	6250	5000			+
GUR, IB	5500	4400	+	+	+

Obtained results

In the conducted simulation, the level of maritime traffic flows are kept same using historical AIS traffic data from 2018 Jan 15th to Feb 15th. The studied scenarios are given in Table 2. One of main KPIs for icebreaker assistance is average waiting time for each assisted ship, i.e., how much time is needed for merchant ships to wait for icebreaker assistance. Therefore, this will be one of the main outcomes. In addition to this, the icebreaker operation time used in winter navigation system and corresponding fuel consumption are also outputs from the modelling. Table 3 summarises the obtained results for the average waiting time KPI, indicating that on mild winter scenario 1 is satisfactory, on average winter scenario 2 is satisfactory and on hard winter scenario 3 is satisfactory when the average waiting time is kept less than 4 hours (240 mins).

Although the simulation results show reasonable trend for the scenarios, the modeling of the Estonian winter navigation system still has many limitations and simplifications comparing to the practical working system. The absolute values of the waiting time need to be referred to carefully. The icebreaker assistance logic still needs improvements, and the practical icebreaker assistance is affected number of additional parameters. The average waiting time is likely to decrease if the optimal home port or waiting location for IBs can be identified in further detail. Especially in IB Scenario 1, with only one icebreaker in Gulf of Finlaand and Gulf of Riiga respectively, the waiting time is likely to reduce dramatically. In addition, near the coastline, there are possibilities for icebreaking assistance from tugs and channels can also be left open by other ships, which are not able to be included in the simulation. These will also reduce the waiting time in practice. In general, further validation and comparisons with the practical cases are planned in future research for improving the accuracy and resilience of the model.

Table 3: Summary of the main KPI-average waiting time (mins) for all scenarios (Tapaninen et al., 2023)

Scenarios	Mild winter	Average winter	Severe winter
1	130	500	1000+
2	110	160	400
3	110	140	150

DISCUSSION

The developed simulation tool aims to capture all the main elements of the winter navigations system: ice-going ships, icebreakers, varying ice conditions and varying situations for assisting ships in ice. All these elements are challenging to simulate. Ice conditions are dynamic with great variations even for one day. In addition, the idea of using the equivalent level ice thickness to describe various ice conditions with one value aiming to simulate reliably the ship average speed on these ice condition causes a number of challenges. This is due to the fact that evaluation of the equivalent ice thickness needs accurate physics-based models to determine ship performance in varying ice conditions. Historically, ship performance in level ice has been the dominating research area to develop analytical formulation for ship resistance. The other ice conditions, such as ridges, dynamic moving ice, and ice floes with varying concentrations have obtained less attention. Consequently, the methods used to evaluate the equivalent ice thickness for these ice conditions needs further research as well how to link the equivalent ice thickness calculation methods to the main particulars of the ice-going ships.

Another important area for further development is how to simulate the decision-making process of icebreaker captains coordinating the whole maritime operations during wintertime. This has crucial effect on the efficiency of the winter navigation system. This decision-making process should include knowledge of a number of parameters like: summary of the ships and their ice-going performance being or approaching the studied area, most probable development ice conditions in near future, available ice-breakers on the area and their location and duties in near future etc. On the present form the tool is using mainly the maximum waiting time for ice-going ships as the main decision-making criteria, which is naturally too simple.

However, the first results of applying the system level simulation tool are promising even though of the prevailing challenges describe above. This is unique tool worldwide trying to simulate all the main elements of the winter navigation system. On system level the average waiting time for ships have been obtained with less than 10 % accuracy. Comparing the ship arrival time to harbors the scatter has been much wider caused mainly by the limitations on the factors: Icebreaker decision making, winds and currents impact on the ice movement not included, optimized utilization of ice channels not included, only one speed threshold for the icebreaker assistance is included and inaccuracies on the used hv curves. All these topics will need further development in near future.

CONCLUSIONS

We have developed during the last 10 years a simulation tool to study in the system level the performance of our winter navigation activities. The main aim of the tool development has been to develop a research-based prototype that can be used to simulate the need of icebreakers in the future when both ice conditions, maritime traffic and characteristics of ice-strengthened ships will be under dynamic change. In this paper, the current status of the simulation tool is shortly described together with the main structure and elements of the tool. Some recent case studies with the tool are also summarised: Validation of the tool, optimization of icebreaker assistance for sustainable shipping and analysis of the icebreaker needs in Estonia.

The tool has been applied with success to analyse the wintertime marine traffic both on the Bay of Bothnia for Finnish marine transport and for Gulf of Finland for Estonian marine transport. On system level the accuracy (e.g., the average waiting time of ice-going ships) has been found adequate, but create variation can take place on the voyage based comparisons. The validation of the simulation tool with AIS data to determine the arrival times to harbors shows extensive scatter as the used methods to determine equivalent ice thickness with a reliable link to the used hv curves as well the ice-breaker decision making needs further development.

CONTRIBUTION STATEMENT

Kujala, P.: Conceptualization; methodology; writing – original draft. **Kulkarni, K.:** simulation tool development, review and editing, **Kondratenko, A.:** sustainable shipping part development review and editing, **Lu, L.:** dynamic ice part development, review and editing., **Winberg, C.**: validation part development, **Li, F.:** hv curve development, review and editing, **Musharraf, M.**: supervision, review and editing.

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