Proceedings of the 2022 Winter Simulation Conference
B. Feng, G. Pedrielli, Y.Peng, S. Shashaani, E. Song, C.G. Corlu, L. H. Lee, E.P.Chew, T. Roeder, and P. Lendermann, eds.

SYSTEM-LEVEL SIMULATION OF MARITIME TRAFFIC IN NORTHERN BALTIC SEA

Ketki Kulkarni
Fang Li
Cong Liu
Mashrura Musharraf
Pentti Kujala

Marine Technology
Aalto University
Tietotie 1C
Espoo, FINLAND

ABSTRACT

Maritime traffic in winter in the Baltic Sea (particularly the northern part) is challenged by heavy ice formation. Icebreaker ships that can provide assistance are a limited resource that need to be shared among all ships. Decision-making for winter navigation systems thus involves monitoring several parameters at both operational and system level, including multiple stochastic parameters. This work presents an integration of ice characteristics, operational level details of ships, and system level details such as traffic flows and icebreaker scheduling through a simulation framework. At the core is a discrete-event simulation model that mimics winter traffic flows in varying ice conditions obtained through meteorological data. This work brings in the novel combination of using ship-level research (operability of individual ships in different ice conditions) as an input in deriving vessel speeds for modelling traffic flows for system-level optimization.

1 INTRODUCTION

The Baltic Sea is an important socio-economic region for the countries around it. Not only is it a critical mode of transport of goods and services, but it is also a sensitive ecosystem of flora and fauna. The Baltic Sea Region (BSR) experiences long and harsh winters that affect the lives of all involved. Despite the weather, maritime traffic continues in the winter months, bringing in essential supplies to the countries. The northern part of the Baltic Sea, the Bay of Bothnia, is covered with ice first and stays frozen the longest. The region also experiences heavy ridged ice formation. Many of the merchant vessels navigating through this region do not have sufficient ice-breaking capabilities to move through such conditions. They often require the assistance of icebreaker ships, that can break the ice and form directed ways (or dirways) through the ice-covered sea on which the vessels can navigate (Hakola 2020).

The icebreakers are a shared resource among all the vessels that ensure safety and efficiency of the winter navigation system. The ice-breaking capabilities differ among ships as the joint result of available power and hull form. Hence, some vessels require icebreaking assistance sooner than the others. Vessels are required to wait at safe stopping points (waypoints) for icebreakers to arrive. The winter navigation system (WNS) aims to reduce the waiting times of vessels as much as possible. The icebreakers are also an expensive resource and hence the WNS aims to use them prudently. This makes decision-making for such systems a complex problem that requires monitoring several parameters, including stochastic parameters, such as waiting times at ports and icebreaker maintenance downtimes.

Due to the rapidly changing climate and effects of global warming, ice conditions in the polar regions and in the BSR are changing. It has become important to study the future of ice condition and how it will impact maritime traffic in the years to come. Further, in an effort to combat climate change, International Maritime Organization (IMO) has been revising their policies ("Energy Efficiency Measures" n.d.) to make navigation more emission compliant. Part of these measures would result in future vessels having lesser icebreaking capabilities, implying that they would need more assistance during winter navigation.

An important decision for traffic controllers in the BSR has always been about the availability of icebreaker ships during winter. It will be crucial to study how the icebreaking needs, and capabilities will change along with the changing ice conditions. There have been several studies that have estimated the future ice conditions as a result of climate change (Höglund et al. 2017). There has also been significant research on ship designs for ice navigation (Trafi, n.d.). In the research work presented in this article, insights from multiple of these prior research efforts on ice conditions, vessel performance and traffic management have been combined to build a holistic winter navigation system. A simulation model is at the core of this system, which incorporates data from multiple sources and uses many smaller functionalities to create a powerful visualization of the traffic flows and ice conditions together. The simulation model allows for testing several hypothetical what-if scenarios that help gain insights on how future traffic maybe affected by changing ice. Simulation of a single winter period enables to capture in detail the weather-wise ice variations (daily changes) and behavior of icebreakers in response to vessel movements. Comparing multiple winters allows for a study of impact of climatic changes. The functionalities enable easier monitoring of Key Performance Indices (KPI), not just at the end of the of the period, but throughout the simulation run.

The main contribution of this research is the framework for modelling a complex traffic and environment system. It includes amalgamation of several data sources in a tangible manner to create an easy-to-use and easy-to-follow simulation-based tool. The challenges involve identifying the causal effects of the environmental factors on the traffic flows and making necessary approximations to incorporate them in the navigation system. Appropriate expressions are modelled to create realistic responses of traffic entities to the environmental changes. The framework is designed to be flexible and scalable, being able to incorporate the entire winter period (6 months) if required. The primary intended function of this model is to run different input scenarios (including variation of time period, number of vessels, number of icebreakers and ice conditions) and compare the outputs (KPI of average waiting time categorized by vessel, port and icebreaker). The quantitative analysis thus involves field experts comparing the outputs of hypothetical scenarios to get a better understanding of the system.

This article introduces the simulation framework and presents its application in evaluating effects of ice variation on the traffic flow. The different modelling aspects are described in detail, along with their implementation. Some of the parameters of the model are introduced and preliminary experiments to prove the efficacy of design are presented. The detailed verification, validation and parameter variation experiments pertaining to the simulation model are beyond the scope of this article and will be presented in an extended journal version.

2 RELATED WORK

This section presents some of the results for the literature review of scientific work in similar areas. Marine traffic is highly important to the BSR, where goods and services depend on the seas all throughout the year. Some parts of the BSR may remain frozen from anywhere between 3 to 6 months (Hakola 2020). For this reason, navigation in ice is a highly researched topic in BSR. There are several aspects to studying ice in the seas such as its concentration, movement, topography, and impact of vessel designs on icebreaking. There are also studies directed towards predicting the future of ice formation, given the climate change and global warming. The work presented in this paper aims to use the insights from some of these diverse research efforts and bring them together in a tool that can be used for scenario testing.

There are many groups of researchers who have combined Automatic Identification System (AIS) data with ice data and performed analyses to gain insights into traffic patterns. (Stocker, Renner, and Knol-Kauffman 2020) have chosen the Svalbard area and researched the data from 2012-2019 for changing ice patterns. The authors have used time series analysis to determine vessel movement trends in response to decreasing Arctic ice. The results help identify which kinds of vessels have increased activity in the Arctic (cruise and fisheries) and the potential dangers to environment. (Goerlandt et al. 2017) have analyzed ice data variations and their impact on convoy operations and escort journeys in winter navigation. Although they do not consider the WNS traffic flows in entirety, they have evaluated in detail the distances between vessels and icebreakers in convoy and escort situations. The visualization is in the form of videos constructed of convoy operations. (Montewka et al. 2016) provide a useful study of various modelling approaches for traffic flows in varying ice. Their comparison of engineering-based and data-driven approaches brings out several important factors that need to be addressed while capturing the complex WNS. A ship-specific hybrid model is also proposed, drawing on the strengths of each type of modelling approach. (Guinness et al. 2014) have combined four types of models (ice, ship performance, sea spatial and ship maneuverability) along with the A* algorithm to develop a route optimization model. (Stoddard et al. 2016) have visualized routes on risk maps for the Canadian Arctic region. Although they do not consider full-fledged traffic flows, they have analyzed ice charts and vessel dimensions to visualize ship operational limits along a large area of interest on a particular route. (Pizzolato et al. 2014) have performed correlation studies to find the relationships between ice variation and maritime traffic. They do not capture traffic flows but show the effect of ice on different vessel types and their counts.

There have been some previous efforts to use simulation models in winter navigation. Notably, (Lindeberg et al. 2018) and (Bergström and Kujala 2020) have built simulation models for the Finnish-Swedish WNS. They both have used AIS and ice data to create an environment for vessels to move as per their schedules during the winter months. While (Lindeberg et al. 2018) consider icebreaker scheduling and convoy formations, (Bergström and Kujala 2020) do not consider convoys. Neither of the two simulations visualize the traffic flows. The results are in the form of log files with statistics on waiting times. (Höglund et al. 2017) have used statistical simulations to study historical ice data and predict future ice conditions. While traffic flows based on AIS data are not included, some discussions are presented on how navigation and restrictions may be impacted. (Etienne and pelot 2013) have presented a simulation tool that analyzes feasible paths based on varying ice conditions in the Arctic. They rely of Dijkstra's algorithm for shortest path analysis based on ice charts. Table 1 provides a summary of the articles reviewed and discussed in this section.

Table 1: Summary of literature review

Author	**Simulation**	**Ice data**	**Traffic flows**	**Visualization**	**Evaluation***
(Stocker, Renner, and Knol-Kauffman 2020)	x	✓	✓	x	✓
(Bergström and Kujala 2020)	✓	✓	✓	x	✓
(Lindeberg et al. 2018)	✓	✓	✓	x	✓
(Höglund et al. 2017)	✓	✓	x	x	✓
(Goerlandt et al. 2017)	x	✓	x	✓	✓
(Stoddard et al. 2016)	x	✓	x	✓	x
(Montewka et al. 2016)	x	✓	x	x	✓
(Pizzolato et al. 2014)	x	✓	x	x	✓

(Guinness et al. 2014)	x	✓	x	x	✓
(Etienne and pelot 2013)	✓	✓	x	x	✓
Presented work	✓	✓	✓	✓	✓

*Evaluation of the impact of ice variation on traffic flows or navigation

Many of the prior research works focus on route optimization or vessel specific research. With this work, we aim to capture not just specific routes or vessels, but the entire traffic flows during the winter period, which includes all the vessels that have visited the area of interest. The dirways are not fixed but changed periodically to replicate the real-life behavior. Prior work on vessel speeds is incorporated to realistically capture changing speeds in response to varying ice. A simulation framework lends itself naturally for modelling a complex problem such as the winter navigation. Compared to the previous simulation work in winter navigation, the work presented in this paper shows clear visualization and capturing of more detailed system behaviors, allowing for a more thorough evaluation of ice variation impact.

3 MODELLING APPROACH AND SCOPE

The simulation model offers a platform to combine information from different sources: ice conditions, traffic flows, resource availability and operating strategies. The model has been implemented using the AnyLogic® software, with additional functionalities coded in Java. A multi-level simulation model has been implemented. Each level of simulation is a layer of the model, with mutually exclusive details. The term "level" is used for consistency with the AnyLogic® software, where entities must be placed in a level. It is possible to run each level as a separate simulation model. In the first level, the environment in which the entities move is created. This consists of geographical coordinates and the ice thickness at those points. The ice data currently include only thickness and concentration. In future, available sources and methods will be investigated to locate ice channels into the system and define the ice thickness in the channels. Ice channels are formed when ships break through intact ice, leaving a channel which is easier for other ships to go through. Ice drifting is another factor which affects the performance of ships through ice. Ice drift includes movement of ice that is not fastened to a shoreline due to sea currents and wind factors. Currently the ice data do not offer parameters describing the drifting of ice. But in future ice drifting data will be

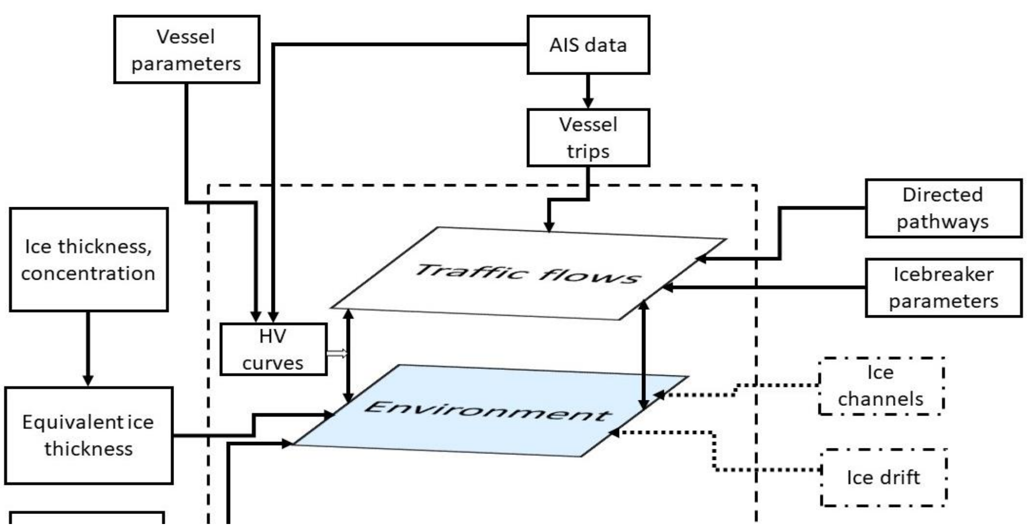

Figure 1: Model framework.

available and added to the simulation program. Equivalent ice thickness is calculated using ice thickness and concentration values. When the environment level is run by itself, it is possible to view the varying ice conditions across the region during different time instances of the winter period.

In the next level, the directed pathways (dirways) and ports are placed to enable modelling of traffic flows. The information about dirways is obtained through data sources provided by the field experts. Vessels and icebreakers are also placed in this level, along with the information about their schedules (trips) and other parameters such as icebreaking capabilities and engine power. The AIS data is processed to obtain vessel-wise trip information. Icebreaker parameters are provided by the experts. When this level is run by itself, the traffic flows are created, where the vessels follow a schedule for visiting ports at a constant speed (open water speed). The link between the two levels is the hv-curves, which are polynomial expressions relating equivalent ice thickness with vessel parameters. Vessels are assigned a set of hv-coefficients based on their dimensions. Vessel speed is evaluated at timed instances to capture the effect of changing environment using the hv-coefficients in the hv-curve expressions. This, in turn, affects traffic flows and triggers assistance calls to icebreakers, which sets them in motion. Figure 1 shows a schematic diagram of this framework along with the various data sources and their interactions. The two primary sources of data are the AIS and ice data. They are processed to obtain inputs for the simulation model such as vessel trips and equivalent ice thickness. This is explained in detail in the next section.

Although the simulation framework being developed is applicable for the entire BSR, the case study presented in this paper focuses on the Bay of Bothnia, the northernmost part of the Baltic Sea. The traffic data for 1 month (from 15 January to 15 February 2018) is included in the case study. All traffic originating or terminating outside the region of observation is assumed to enter and exit the area of interest from the South, from the Kvarken archipelago. The ice conditions are available for every 1 square nautical mile and for every hour of every day in the 1-month period. However, to ease the computational load during runtime, the ice conditions are updated once every day (at noon). Based on discussions with expert mariners at the Finnish Transport Infrastructure Agency, this is a realistic assumption that is not expected to adversely affect the simulation. The model captures ice navigation in detail including convoy operations, where an icebreaker may assist a group of vessels together. The vessels follow the icebreaker, one behind the other, and the convoy moves together at one common speed.

4 MODEL DATA

The two primary sources of data are the AIS data and the ice information. The ice data is required to create the right environment for the entities (vessels) to exist in, in the simulation model. The AIS data is used to build the traffic flows for the entire period. In this section, more information is presented on how the data is processed and used in the simulation model.

4.1 Traffic flows from AIS data

The AIS data includes high frequency pings that are collected by AIS receivers on land. Vessels transmit their information (pings) to these receivers. Ports, icebreakers, and other vessels can view this information through their own receivers to gauge the traffic. For the purpose of the simulation model, it is important to extract vessel itineraries for the duration of interest. This includes trip origin, time of departure from origin, and destination port. A vessel typically makes multiple trips during the month between different ports. Table 2 shows the columns in the processed AIS data, exported as excel files. The vessels are identified using MMSI numbers. Based on the Latitude-Longitude information, the starting and destination ports are identified, by matching them to the coordinates of the closest port. The start time or departure time from the ports is an input to the model. The end time or arrival time, although available, is not used as an input. The vessels move in the system based on the logic in the statecharts and their simulation arrival times are noted. These are then used in validation studies.

Table 2: Processed AIS data.

MMSI	OrigPort	Lat_Orig	Lon_Orig	StartTime	DesPort	Lat_Des	Lon_Des	EndTime
xxxxx	Oulu	65.01	25.45	dd-mm-yy hhmm	Roytta	65.75	24.15	dd-mm-yy hhmm

4.2 Ice data from multiple sources

The ice data is obtained from the Finnish Meteorological Institute (FMI). The information is available in two formats: SIGRID-3 and NetCDF. The speed of the vessels changes in response to the change in ice conditions.

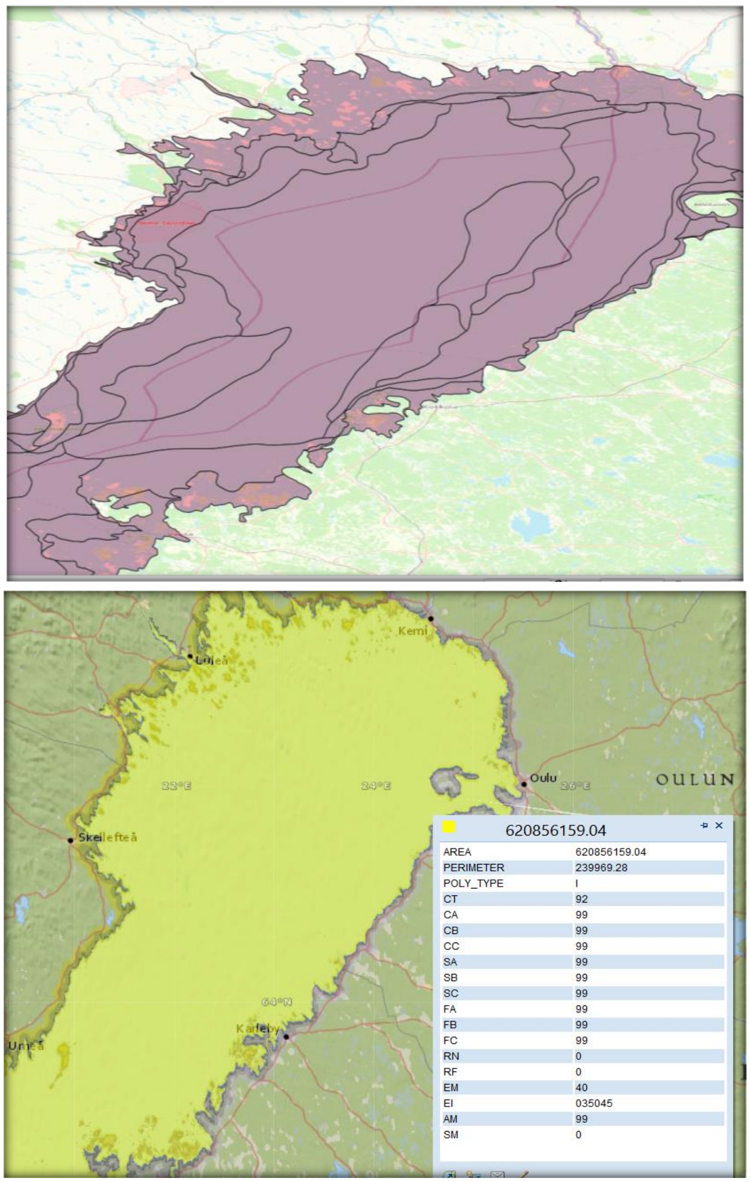

Figure 2: SIGRID-3 ice data a) Polygons b) Ice parameters for polygon.

This relation is determined by hv-curves, which indicate the attainable speed of ships in level ice of certain thickness (Lindeberg et al. 2018). Figure 2 shows the data from the SIGRID-3 format, as viewed through the QGIS® software. In Figure 2a, the polygons are visible across the region selected. Each polygon represents a geographical area that is characterized by similar ice conditions. In Figure 2b, a sample of the ice conditions is shown by hovering over a geographical point on the map. The information includes ice concentration, thickness, and topography. More details can be found in World Maritime Organization (WMO) document on ice data (Ice 2014)The ice data in NetCDF format including ice thickness and concentration parameters are presented with 1 NM-by-1 NM spatial resolution and one hour temporal resolution by Nemo-Nordic operational marine forecast ice model. The details of the ice forecast model are described in (Kärnä et al. 2021). The data are more detailed geographically but contain lesser information on topography, e.g., existence of ice ridges. The data is processed into excel files in table format as shown in Table 3. The ice thickness value is obtained for every hour of every day, for every latitude-longitude combination in the region. The ice thickness is the equivalent ice thickness, obtained by averaging the ice volume over that area. The approach to calculating equivalent ice thickness is similar to (Lindeberg et al. 2018) and (Bergström and Kujala 2020).

Table 3: Processed NetCDF ice data.

Latitude	Longitude	Timestamp	Ice thickness
53.82	13.86	20180115 1200	0.0495

It is observed that for the case study under consideration, the ice variation is not severe across the hour. Hence the ice conditions in the model are updated once every day, instead of every hour. It is, however, possible to change the updating frequency for other case studies.

5 SIMULATION FRAMEWORK

The simulation environment is modelled as a multi-level environment. A grid is created to capture the latitude-longitude based ice data and represent it in a row-column format in the model.

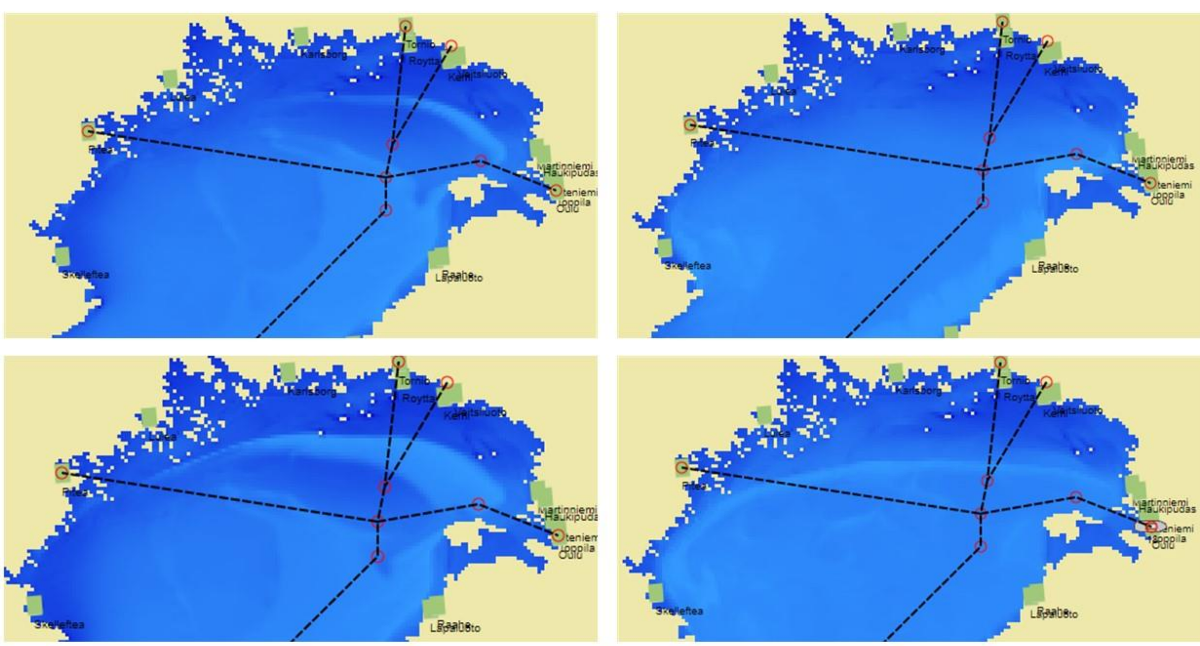

Figure 3: Varying ice conditions across the winter.

Each cell of the grid represents one geographical point from the ice data. Each grid cell is also modelled as an agent with parameters capturing the ice conditions. A Java function assigns a color to the cell during model run time, based on the value of ice thickness. As the ice thickness of the cell varies, so does the color of the cell, giving a visual appearance of changing ice. Figure 3 shows the modelling of the multi-level environment in detail. Figure 3 shows the variation in ice conditions visualized by the changing shades of blue for time instances on 6 different days between 15 January and 1st February 2010. The pale-yellow area is the land surrounding the Bay of Bothnia (Finland and Sweden). The black dashed lines are the dirways created by the maritime infrastructure authorities using icebreakers for the navigation of the vessels. The red circles are the waypoints where vessels may stop safely while waiting for assistance.

The entities of the WNS, for example, the vessels and icebreakers, are modelled as agents. Their decision-making is captured through statecharts. The ports and waypoints are also modelled as agents.

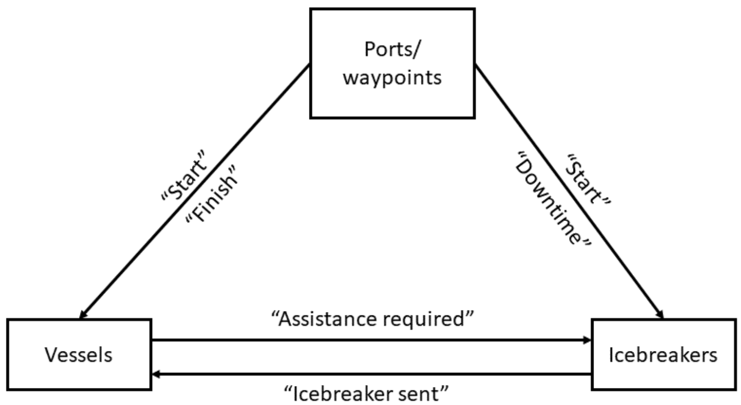

Figure 4: Communication between agents.

However, instead of statecharts, there are process flow charts to determine the sequence of actions that take place at these locations. All agents communicate with each other throughout the model run. Figure 4 shows the communication messages between the agents. The ports send the first message "Start" at the start of the simulation run, which places all vessels and icebreakers at their initial locations (either a port or a waypoint). Based on their individual schedules, vessels continue to navigate through the system until they encounter ice that is too thick for them to maintain their speed above a threshold. At this point, they send a message "Assistance required" to the icebreakers. These messages are not sent to an individual icebreaker, but to a controller that the entire fleet of icebreakers can access. The icebreaker most suited for assisting the vessel is chosen and it responds to the vessel with a message "Icebreaker sent". Along with the messages, information about location of the agent and the ice thickness at the location is also shared. When a vessel finishes all their trips for the period, the final port in their itinerary sends a "Finish" message and moves the vessel out of the system. Every icebreaker has a scheduled downtime, typically once every 10 days, for half a day. The port where an icebreaker needs to go for maintenance/downtime sends a message "Downtime" to the icebreaker.

There are several events that take place during the winter period. Some other events are dynamic, which occur as a response to change in parameters. Table 4 lists some of the important events in the model. The ice conditions are updated every 24 hours using the equivalent ice thickness values in the database. Once this event is triggered, all vessels and icebreakers recalculate their speeds. The environment (level 1 of the simulation) updates the visualization based on the new ice thickness values. When no other event is triggered and the vessels are moving along at a steady pace, the speed change event is triggered every 30 minutes. The speed of the vessels and icebreakers is recalculated based on the ice thickness of its current location. When the speed of a vessel drops below a specified threshold (3kn for the case study), the request assistance event is triggered. A message is sent to the nearest icebreaker and the vessel is made to wait at a safe stopping point for the icebreaker to arrive. When the icebreaker reaches the vessel to assist, the "assistance mode on" event is triggered. The icebreaker and the assisted vessel are both assigned a common speed, based on the ice conditions and the vessel and icebreaker dimensions.

Table 4: Events in simulation model.

Event	*Trigger*	*Entity affected*
Update ice conditions	Cyclic (24 hours)	Environment, vessels, icebreakers
Speed change	Rate (30 minutes)	Vessels, icebreakers
Request assistance	Condition (speed < threshold)	Vessels
Assistance mode on	Message (IB received)	Vessels, icebreaker

At the ports and waypoints in the system, the vessels and icebreakers spend some time waiting until their departures. The behavior at these points is modelled as process flows, allowing to capture vessel or icebreaker downtimes, wait for resources (berths at ports or icebreakers at waypoints) and any other delays (due to adverse weather conditions).

6 COMPUTATIONAL EXPERIMENTS

A set of preliminary experiments is designed to test the efficacy of the model and to confirm that it captures the requirements of the stakeholders. A careful observation of the visualization at various time instances is the first step to ensure that the traffic flows, port and waypoint locations and the icebreaker interactions are authentically captured. As mentioned earlier, the case study presented in this article focuses on the Bay of Bothnia. To evaluate the impact of ice variation, different scenarios are created for comparing the system performance.

Table 5 shows the input and output parameters of the simulation model. The minimum speed threshold is the value of vessel speed below which they require icebreaker assistance. Maximum allowable waiting time is the maximum time before which an icebreaker must reach a vessel requiring assistance. The output KPI is the average waiting for the vessels, which is the time that the vessel spends waiting for an icebreaker to assist it. There are different ways in which an icebreaker may choose the next vessel to assist. Different decision-making algorithms have been implemented. However, this article does not present the experiments pertaining icebreaker decision-making. More detailed experiments with parameter variations and other functionalities are presented in the extended version of this article.

Table 5: Parameters in simulation model.

Parameter	Unit	Default value
Input		
Min. speed threshold	kn	3
Max. allowable wait time	Hour	12
Simulation period	Days	30
Number of vessels	-	5,..,10
Number of icebreakers	-	1, 2
Output		
Average waiting time	Hour	--

Table 6 shows the results from the experiments with ice variations. Two environmental conditions are considered: no ice (open waters), and varying ice conditions as per meteorological data. As expected, for open waters, there is no waiting time since the vessels can maintain their speeds and do not need assistance.

Table 6: Impact of ice variation. Number of vessels = 5.

Ice conditions	Number of icebreakers	Average waiting time (minute)
No ice (open waters)	1	0
Varying ice	1	172
Varying ice	2	141

Some waiting time is experienced by the vessels for varying ice conditions. On increasing the number of icebreakers, the average waiting time drops slightly. Even though the number of vessels is small (5), and the resources (icebreakers) are doubled, the average waiting time does not drop significantly. This is because along with the number of icebreakers, their location in the region is also an important factor. Table 6 shows the effect of icebreaker locations and their impact on waiting time. Icebreakers are placed either in the North or South of the region (Bay of Bothnia). If the icebreakers are all concentrated in one area, then waiting times may be higher in other areas. Also, when more than one vessel is waiting for an icebreaker, they need to make a choice about which one to assist first. This decision-making also greatly impacts the overall waiting time experienced by the system.

Table 7: Impact of icebreaker location. Number of icebreakers = 2, Number of vessels = 10.

Icebreaker locations	Average waiting time (minute)
Both in one region (North)	206.28
1 in North, 1 in South	187.93

As seen in the results in Table 7, icebreakers covering a wider area can reduce waiting time. However, some areas have more difficult ice conditions than others and may require more assistance. Detailed experiments are required to determine the number of icebreakers in each region. Also, along with average waiting time, the maximum waiting time is also a metric to be considered. Table 8 shows the impact of ship-level details on the traffic flows. In the first run, all ships are assumed to have identical ice navigation capabilities (high). In the second run, ship-wise hv curves are used.

Table 8: Impact of ship operational details. Number of icebreakers = 2, Number of vessels = 10. Icebreaker locations = 1 North, 1 South.

Ship ice navigation capabilities	Average waiting time (minute)
Identical- high	108.43
Based on hv curves	187.93

It is clearly seen that ship-level details have a high impact on the traffic flows. With these computational experiments, even for a small sample size of 10 vessels and 2 icebreakers, it is demonstrated that system (icebreaker availability, location) and ship level (hv curves) parameters can greatly affect the traffic flows and thereby the resource requirements. These effects are even more pronounced for the full-size data of nearly 1500 ships and 9 icebreakers. Ongoing work in this research includes icebreaker placement and decision-making optimization. The work also involves modelling of change in ship engine power for reduced fuel consumption and its impact on icebreaker requirements.

7 CONCLUSION AND FUTURE RESEARCH

This work presented a simulation-based framework for evaluating the impact of ice variation on maritime traffic. A case study focused on Bay of Bothnia in the BSR was chosen to demonstrate the model. The model uses a multi-level environment to capture ice information along with geographical coordinates and AIS data for vessel trips. The vessels and icebreakers in the system are modelled as agents whose behaviors are governed by statecharts. Using the simulation model to vary the ice conditions, the effects of ice levels on the WNS are quantitatively captured through carefully designed experiments. The model provides a bird's eye view of the WNS and allows for testing what-if scenarios, addressing important decisions about icebreaker availability in the future. The framework designed has been ensured to be easy to use for stakeholders. The system behaviors have been modelled with inputs from experienced mariners and traffic controllers.

The future research would not only involve extending the area to cover the wider Baltic Sea Region, but also add more details regarding special cases such as ship towing. The current KPI is average waiting time. In the upcoming research, variation in engine power of vessels and icebreakers will be added, which will allow KPI based on fuel consumption and CO2 emissions to be included. Variation of engine power allows vessels to control their fuel usage. In the case studies demonstrated in this article, weather-wise change in ice conditions, that is, daily ice variation is captured. As part of future evaluations, seasonal changes in ice will be studied by comparing traffic scenarios for the same time period across different years.

ACKNOWLEDGMENTS

We would like to thank the many organizations and individuals who provided guidance and support throughout this study. From Väylävirasto, we thank Helena Orädd, Tuomas Taivi, Ilari Rainio and Jarkko Toivola. We gratefully acknowledge the funding by the Winter Navigation Research Board, a Finnish–Swedish cooperation co-funded by the Finnish Transport and Communications Agency, the Finnish Transport Infrastructure Agency, the Swedish Maritime Administration, and the Swedish Transport Agency under the projects WinterSim and SIMNAV.

REFERENCES

Bergström, M., and P. Kujala. 2020. "Simulation-Based Assessment of the Operational Performance of the Finnish–Swedish Winter Navigation System." *Applied Sciences* 10 (19): 6747. https://doi.org/10.3390/app10196747.

"Energy Efficiency Measures." n.d. Accessed March 17, 2022. https://www.imo.org/en/OurWork/Environment/Pages/Technical-and-Operational-Measures.aspx.

Etienne, L., and R. Pelot. 2013. "Simulation of Maritime Paths Taking into Account Ice Conditions in the Arctic." In *11th International Symposium for GIS and Computer Cartography for Coastal Zone Management (CoastGIS)*. Victoria, Canada. https://hal.archives-ouvertes.fr/hal-01740751.

Goerlandt, F., J. Montewka, W. Zhang, and P. Kujala. 2017. "An Analysis of Ship Escort and Convoy Operations in Ice Conditions." *Safety Science* 95 (June): 198–209. https://doi.org/10.1016/j.ssci.2016.01.004.

Guinness, R. E., J. Saarimäki, L. Ruotsalainen, H. Kuusniemi, F. Goerlandt, J. Montewka, R. Berglund, and V. Kotovirta. 2014. "A Method for Ice-Aware Maritime Route Optimization." In *2014 IEEE/ION Position, Location and Navigation Symposium - PLANS 2014*, 1371–78. https://doi.org/10.1109/PLANS.2014.6851512.

Hakola, V. 2020. "Predicting Marine Traffic in the Ice-Covered Baltic Sea." https://trepo.tuni.fi/handle/10024/120219.

Höglund, A., P. Pemberton, R. Hordoir, and S. Schimanke. 2017. "Ice Conditions for Maritime Traffic in the Baltic Sea in Future Climate" 22: 21.

Ice, JCOMM Expert Team on Sea. 2014. "SIGRID-3 : A Vector Archive Format for Sea Ice Georeferenced Information and Data. Version 3.0." Report. WMO & IOC. https://doi.org/10.25607/OBP-1498.2.

Kärnä, T., P. Ljungemyr, S. Falahat, I. Ringgaard, L. Axell, V. Korabel, J. Murawski, et al. 2021. "Nemo-Nordic 2.0: Operational Marine Forecast Model for the Baltic Sea." *Geoscientific Model Development* 14 (9): 5731–49. https://doi.org/10.5194/gmd-14-5731-2021.

Lindeberg, M., P. Kujala, O.-V. Sormunen, M. Karjalainen, and J. Toivola. 2018. "Simulation Model of the Finnish Winter Navigation System." In *Marine Design XIII*. CRC Press.

Montewka, J., R. Guinness, L. Kuuliala, F. Goerlandt, P. Kujala, and M. Lensu. 2016. "Challenges in Modelling Characteristics of Maritime Traffic in Winter Conditions and New Solution Proposal." In *Maritime Transportation and Harvesting of Sea Resources*, 247–56. https://research.aalto.fi/en/publications/challenges-in-modelling-characteristics-of-maritime-traffic-in-wi.

Pizzolato, L., S. E. L. Howell, C. Derksen, J. Dawson, and L. Copland. 2014. "Changing Sea Ice Conditions and Marine Transportation Activity in Canadian Arctic Waters between 1990 and 2012." *Climatic Change* 123 (2): 161–73. https://doi.org/10.1007/s10584-013-1038-3.

Stocker, A. N., A. H. H. Renner, and M. Knol-Kauffman. 2020. "Sea Ice Variability and Maritime Activity around Svalbard in the Period 2012–2019." *Scientific Reports* 10 (1): 17043. https://doi.org/10.1038/s41598-020-74064-2.

Stoddard, M. A., L. Etienne, M. Fournier, R. Pelot, and L. Beveridge. 2016. "Making Sense of Arctic Maritime Traffic Using the Polar Operational Limits Assessment Risk Indexing System (POLARIS)." *IOP Conference Series: Earth and Environmental Science* 34 (1): 012034. https://doi.org/10.1088/1755-1315/34/1/012034.

Trafi, Finnish Transport Safety Agency. n.d. "Ice Class Regulations and the Application Thereof." Helsinki: Finnish Transport Safety Agency. https://www.finlex.fi/data/normit/43682/TRAFI_494_131_03_04_01_00_2016_EN_Jaaluokkamaarays_2017.pdf.

AUTHOR BIOGRAPHIES

KETKI KULKARNI is a research fellow in Marine and Arctic Technology at Aalto University. She is currently working on building decision support capabilities for winter navigation using simulation-optimization techniques. She specializes in the use of advanced simulation software for industrial applications. Prior to this, she worked in Singapore Management University, where she managed the design and implementation of a decision support tool for port gate management. She had obtained her PhD in IEOR, IIT Bombay. She is not only interested in contributing to the methodology literature, but also in developing efficient tools that are used by organizations for their daily operations. She finds packaging the research work (mathematical and simulation models) into usable solutions exciting and challenging. Her e-mail address is ketki.kulkarni@aalto.fi.

FANG LI obtained his D.Sc. degree from the Marine Technology Group of Aalto University and has worked as post-doctoral fellow since December 2020. His field of specialization is Arctic marine technology. Prior to the doctoral period, he received his BE degree from Dalian University of Technology, China on Naval Architecture and Ocean Engineering, and M.Sc. degree from the Nordic master program at NTNU and Aalto on Maritime Engineering. His research interests are ice-going ship performance simulation, ice load estimation and winter navigation. His email address is fang.li@aalto.fi.

CONG LIU is a doctoral candidate studying at Marine Technology Group, Department of Mechanical Engineering, Aalto University. The main task of her work focuses on intelligent winter navigation. Big data analytics and machine learning methods are implemented. Her research aims to help mariners and maritime management authorities better understand the winter operations and support the development of intelligent decision-making system for winter navigation. Her e-mail address is cong.1.liu@aalto.fi.

MASHRURA MUSHARRAF joined the Marine Technology group at Aalto University in early 2021 as an Assistant Professor. She received her PhD (2018) and M.Eng. (2014) in Computer Engineering from Memorial University of Newfoundland, Canada. She has been an active researcher since 2012 with a vision to apply data mining, machine learning, and AI techniques to build and deploy human-centered systems and solutions and create a safer marine industry. Her expertise includes knowledge elicitation from subject matter experts, human performance data collection by conducting full-scale experiments in marine simulators, integration of different data types, and predictive and diagnostic data analysis using machine learning methods. The choice of the analytic tools used in her research is heavily influenced by their interpretability. As the foundations for futuristic ships are being set, her current and future research aims to achieve interpretability and transparency of the AI algorithms that would govern the decision-making in ship design and operation. Her e-mail address is mashrura.musharraf@aalto.fi.

PENTTI KUJALA is a professor of Marine technology and the former head of Marine Technology research group. He is working on the safety of ships both in open water and in ice. His main research interests during a 40- year long career have been devoted to full scale measurements of ice induced loads and analysis of the ice load statistics, simulation of ship performance in ice, development of advanced structural solutions for ships and development of system level safety of marine traffic. His email address is pentti.kujala@aalto.fi.