Anisotropic secondary phases in Mo(Si,Al)2 ceramics investigated by neutron diffraction

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Maritime Transport System Simulation for Sustainable Winter Navigation

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Abstract. The ice presence significantly complicates shipping in cold regions during winter or even year-round in some polar areas. Climate change contributes to a warmer climate, resulting in more favorable ice conditions for navigation and attracting more vessels in cold regions. Efficient ice navigation requires a systemic approach, allowing for planning and analyzing future navigation under complex and changing circumstances. We developed an agent-based simulation tool for the analysis and design of sustainable winter navigation systems, considering the ice conditions, the technical parameters of ships in the traffic, parameters of ship voyages, established maritime routes in the region, and supporting infrastructure (e.g., availability and technical parameters of icebreakers, icebreaking assistance, and ice routing provided by the authorities). This paper presents an overview of the applications of our decision support tool for different regions of the Baltic Sea (e.g., modeling the Finnish-Swedish winter navigation system in the Gulf of Bothnia and winter navigation in the Estonian waters), supporting sustainable, safe, and cost-efficient shipping in ice.

Keywords: arctic shipping · simulation · the Baltic Sea · winter navigation · sustainable · cold regions

1 Introduction

Maritime transportation is the backbone of global trade and is the most productive, cost- and environmentally efficient mode of transporting goods. Ships and their crews have to face and endure many challenges of maritime shipping, like severe storms, poor navigation conditions, dense ship traffic in limited water areas, and piracy threats. When shipping occurs in cold regions, ice indeed is one of the most significant challenges for maritime navigation, especially for areas within or close to the Arctic and Antarctic circles. The corresponding complications for shipping depend on the severity of ice conditions, which is usually correlated with how cold the region is. Naturally, different ice conditions require different design, operation, and regulation solutions for efficient, sustainable, and safe navigation [1, 2]. For example, if the specific navigable water area

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freezes for a short time during the year or the ice is thin and weak, limited strengthening of ship hulls, compared to the open-water-designed ships, may be enough to handle the issue. Ice-strengthened ships are classified into ice classes [3], typically according to their hull strength—improved for ice-going vessels to avoid hull damage—and the available propulsion power needed to break through the ice. However, if the ice conditions are severe or present for a prolonged period, meticulous consideration of all available mitigation options is required.

Effective navigation in ice can be achieved by providing ships in the traffic with icebreaking capabilities that are high enough for independent navigation, reducing their open water efficiency. However, this solution is not always cost- and environmentally efficient for the lifecycle of a ship, especially when ice presence is significant (e.g., the ice is thick in winter) and dynamic during the year (e.g., the period without ice cover is long). The opposite alternative—developing comprehensive icebreaking assistance with strong and powerful icebreakers and advanced operation solutions like ice routing and convoy planning so that even ships with low ice class can operate safely—may also be economically and environmentally expensive, especially if large water areas must be serviced. Moreover, if ice is present for a limited time during the year, e.g., a few months, the icebreakers are idle most of the year if not used in other colder regions, incurring significant costs. Finding the balance between these two major mitigation options is a complex engineering, operational, and regulation issue. Irrespective of the employed strategy, the minimum ice class of a ship for navigation in specific regions, seasons, and ice conditions is regulated on design [4] and operation levels [5].

From the operations perspective, the optimal decision-making for the winter navigation system (WNS) heavily depends on three major external factors: ice conditions (i.e., the spatial distribution of ice with specific parameters and how they change in time), the prevailing icebreaking capabilities of the ship traffic and its density, and the available icebreakers. The authorities are responsible for providing reliable and timely ice data, which accounts for up to 75% of the uncertainty in predictions of ship performance in ice [6]. The organizational and operational decision-making considers, for example, spatial allocation of the available icebreakers, the principles of icebreaker operations—whether an icebreaker supports an ice channel or assists vessels, which vessels are assisted and how (e.g., individually or in convoy), and who decides the assistance (e.g., an icebreakers crew or the specialized center of operations), whether the ice-routing is provided and how (e.g., individually [7] or as regularly published recommended routes [8]).

The issues of ice navigation make the design and operation of the WNS extremely complex, which requires a holistic and systemic approach considering many factors. The connectivity of the cold regions and the ability to guarantee non-disruptive supplies of goods depends on the reliability and performance of shipping in ice. We developed an agent-based simulation tool for the analysis and design of sustainable winter navigation systems considering the corresponding specifics and challenges, e.g., the ice conditions, the technical parameters of ships in the traffic, parameters of ship voyages, established maritime routes in the region, and supporting infrastructure (e.g., availability and technical parameters of icebreakers, icebreaking assistance, and ice routing provided by the authorities). The tool is designed to potentially model a diverse spectrum of ice navigation specifics and issues, so application in a new context can be made with limited adjustments.

This paper presents an overview of the applications of our decision support tool for different regions of the Baltic Sea (e.g., modeling the Finnish-Swedish winter navigation system in the Gulf of Bothnia and winter navigation in the Estonian waters), supporting sustainable, safe, and cost-efficient shipping in ice.

The remainder of the paper is organized as follows. Section 2 describes the materials and methods—theoretical approaches, procedures, and data used in the developed simulation tool. Section 3 presents the existing applications of the tool to improve the efficiency of winter navigation in different regions of the Baltic Sea. Section 4 discusses the strengths and limitations of the developed tool and recommends promising directions for the development and applications of agent-based simulation for sustainable winter navigation.

2 Materials and Methods: The Simulation Tool

The decision-support tool for the simulation of WNS has been developing since 2015 and has resulted in a series of high-level publications [8–13]. The model was initially established for modeling shipping in the Baltic Sea, considering the Finnish-Swedish winter navigation system (FSWNS) operating in the Gulf of Bothnia as a prototype. The FSWNS has the most developed and organized icebreaking assistance in the region, mainly because of the high density of ship traffic and one of the most complex ice conditions in the Baltic Sea. The typical vessel in the traffic is a cargo vessel with a relatively low ice class, requiring icebreaking assistance in the Bothnian Bay– the northern part of the Gulf of Bothnia—during the mild winter. Icebreaking assistance in the region is centrally organized and operates with a great degree of freedom: the icebreaker crew decides whether to assist a ship, so assistance for a specific ship is typically not guaranteed. It is reasonable to model such WNS as a service provided by a limited resource of available icebreakers for an ongoing set of entities—ships, which send a service request on a specific trigger event.

The selection of a simulation approach and a particular modeling paradigm is essential because they define the functionality and efficiency of the future decision-making tool. The organizational structure of the FSWNS aligns perfectly with the paradigm of agent-based modeling [14], with particular behavior set for each class of entities, with no preplanning required. The crucial principle of agent-based modeling (see Fig. 1) is that the behavior of a system is not assumed according to specific high-level analytical and statistical equations or data-based black box models, but its performance is modeled based on the dynamic interaction of entities called agents, e.g., a cargo ship, an icebreaker, or a water segment. The agents are placed in a specific limited one- or multidimensional space connected to a separate layer of environment described by a set of dynamic parameters. The environment may include passive or active agents, such as an ice field. The agent-based modeling supports object-oriented programming. A specific class is defined for each agent, which has its unique set of parameters, variables, and methods. According to the object-oriented paradigm, they can be inherited from the parent class. In other words, cargo ships and icebreakers can be modeled as child classes of the Vessel class, inheriting all the features common to all ships yet having other individual features. In some cases, applying multi-method—combining agent-based modeling with discrete-event simulation and system dynamics as submodels can be helpful.

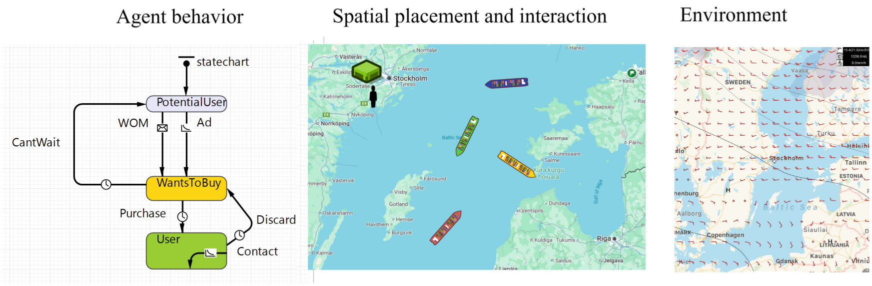

Fig. 1. The basic components of an agent-based model: agent behavior, specified for every type of agent, the space in which the agents are placed and interacting, and the dynamic parameters of the environment.

Figure 2 shows the information structure of the developed simulation model for a Baltic WNS. Corresponding data has to be collected before the model is assembled. The first data layer—Traffic flows—contains information on the ongoing ship traffic within the selected period. The reliable historical data for this layer can be obtained from the Automatic Identification System (AIS) installed on all ships with gross tonnage above 500, all ships with gross tonnage above 300 involved in international shipping, and all passenger ships. The AIS records the information on the current coordinates, activity type, moving direction, and the starting and finish locations of the voyage of a ship. The AIS data comes in different formats—from raw machine-level data to well-presented records—depending on the data source and requires different efforts for processing before it can used in the model [15].

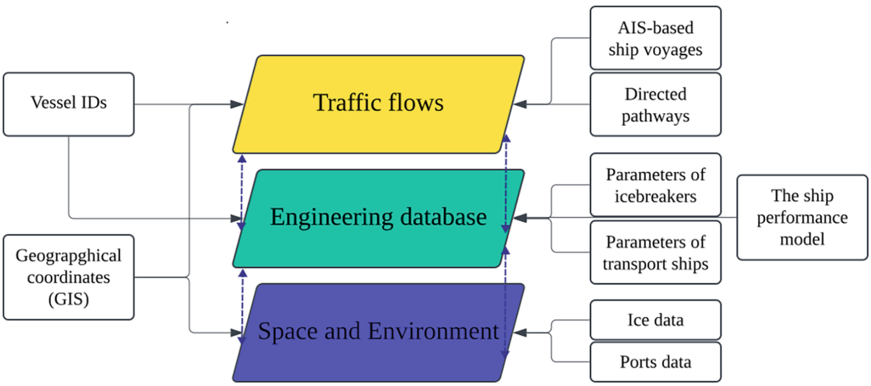

Fig. 2. The information structure supporting the agent-based simulation model of the WNS.

Figure 3 shows an example of the processed AIS data with information on ship voyages needed for simulation and analysis, e.g., coordinates of the start and end points, time of departure and arrival, and IMO number and basic technical information on the ship. Using real-life historical data on ship voyages in the simulation model provides it with digital twin capabilities, allowing for the detailed reproduction of a specific WNS operation period. The departure time starts the simulation of a particular voyage at the corresponding virtual time. The arrival time is used solely for verification.

Besides voyage data, the Traffic flows layer includes information on the directed pathways (dirways), provided as the list of geographical coordinates of consecutive route points recommended for ships to follow during the voyage. Dirways is an ice-routing form typical for the Baltic WNSs, provided by an icebreaker for all ships navigating in a specific area without consideration of their technical characteristics. The icebreaker decides on the dirways and updates them based solely on the parameters of the ice conditions and their dynamic. The historical data on the dirways is used in the tool to simulate the corresponding period.

Start of a voyage	End of a voyage	IMO	Name	Vessel type	Length	Beam	Draught	Start port Lat	Start port Lon	End port Lat	End port Lon	Distance	Time spent	Speed av.
2 03 2018 01:22	2 03 2018 19:11	7816484	AMARANTH	Tanker	118	16	5	59.4872	24.50981	60.36842	26.70754	84.6807764	17.816667	4.7529
9 03 2018 19:18	10 03 2018 16:00	9305568	SCF BALTICA	Tanker	250	44	14	60.0605	27.7515	58.36334	20.6455	240.840949	20.7	11.6348
1 03 2018 08:45	2 03 2018 17:59	9285029	KUJAWY	Cargo ship	190	28	6	58.31233	20.63095	60.1288	27.6378	241.182934	33.233333	7.25726
10 03 2018 13:07	11 03 2018 12:52	9285029	KUJAWY	Cargo ship	190	28	6	60.05542	27.7544	58.16348	20.58095	248.42704	23.75	10.4601
1 03 2018 10:45	1 03 2018 15:09	9307360	KRAFTCA	Cargo ship	205	26	7	60.15578	27.75938	60.48662	26.95011	31.2003017	4.4	7.09098
2 03 2018 23:18	3 03 2018 07:59	9307360	KRAFTCA	Cargo ship	205	26	7	60.43078	26.95514	59.82256	22.94738	125.277149	8.6833333	14.4273
3 03 2018 16:04	3 03 2018 21:52	9307360	KRAFTCA	Cargo ship	205	26	7	59.82306	22.94761	58.43663	20.5869	110.528809	5.8	19.0567
12 03 2018 17:46	13 03 2018 06:25	9307360	KRAFTCA	Cargo ship	205	26	7	58.3228	20.64429	60.42657	26.94598	230.310836	12.65	18.2064
13 03 2018 21:11	14 03 2018 01:15	9307360	KRAFTCA	Cargo ship	205	26	7	60.40882	26.89829	60.06765	27.77271	33.1492262	4.0666667	8.15145
15 03 2018 06:54	15 03 2018 11:26	9307360	KRAFTCA	Cargo ship	205	26	7	60.12999	27.53972	60.42529	26.94434	25.0704852	4.5333333	5.53025
3 03 2018 04:34	3 03 2018 10:30	9250098	CONTAINERSHIPS VII	Cargo ship	158	22	7	60.14904	27.69307	60.21165	25.19357	74.7206915	5.9333333	12.5934
11 03 2018 19:36	12 03 2018 08:42	9250098	CONTAINERSHIPS VII	Cargo ship	158	22	7	58.31945	20.59804	60.21164	25.19359	181.024259	13.1	13.8186
12 03 2018 23:13	13 03 2018 20:15	9250098	CONTAINERSHIPS VII	Cargo ship	158	22	7	60.21164	25.19359	57.03946	24.07016	193.673624	21.033333	9.20794
2 03 2018 03:45	2 03 2018 18:13	9299862	BALTIC ADVANCE	Tanker	181	27	8	59.51617	24.50083	60.15483	27.71117	104.161259	14.466667	7.20009
4 03 2018 04:04	4 03 2018 23:54	9299862	BALTIC ADVANCE	Tanker	181	27	8	60.11967	27.57783	58.3605	20.64733	237.442396	19.833333	11.9719
1 03 2018 12:57	2 03 2018 07:42	9354533	VLADIMIR	Cargo ship:I	184	26	10	58.26383	20.58016	60.16864	27.76692	248.530393	18.75	13.255
1 03 2018 13:09	2 03 2018 07:46	9761176	NAVIGATOR YAUZA	Tanker	160	26	6	58.19906	20.63252	60.16769	27.76052	248.909622	18.616667	13.3703
4 03 2018 03:47	4 03 2018 22:32	9761176	NAVIGATOR YAUZA	Tanker	160	26	6	60.14141	27.69034	58.3175	20.64299	242.441962	18.75	12.9302
12 03 2018 07:29	13 03 2018 00:12	9761176	NAVIGATOR YAUZA	Tanker	160	26	6	58.20055	20.63295	60.06782	27.76282	246.419009	16.716667	14.7409
1 03 2018 14:18	2 03 2018 06:23	9016662	BALTIC PILGRIM	Cargo ship	150	23	8	60.15168	27.69158	58.40372	20.61978	240.820798	16.083333	14.9733
4 03 2018 14:05	5 03 2018 00:54	9226803	KURLAND	Cargo ship	100	16	6	60.41078	26.90288	59.54708	26.53741	53.0092547	10.816667	4.9007
2 03 2018 08:34	2 03 2018 13:04	9297137	LOTUS	Tanker	87	13	5	60.22533	25.58732	60.16382	24.96582	18.9128679	4.5	4.20286
9 03 2018 23:13	10 03 2018 21:41	9255622	LUCINA	Cargo ship	132	16	8	60.07267	27.753	58.32533	20.64167	242.349085	22.466667	10.7871
11 03 2018 17:43	12 03 2018 06:54	9458975	CONMAR BAY	Cargo ship:I	151	24	8	58.3342	20.64348	60.21506	25.18784	179.347848	13.183333	13.6041
13 03 2018 06:35	13 03 2018 13:09	9458975	CONMAR BAY	Cargo ship:I	151	24	8	60.21452	25.18971	60.41929	26.91626	52.7872675	6.5666667	8.03867
13 03 2018 23:48	14 03 2018 15:39	9458975	CONMAR BAY	Cargo ship:I	151	24	8	60.41669	26.91622	58.43988	20.60319	226.264707	15.85	14.2754
5 03 2018 23:11	6 03 2018 21:46	9321689	SOLVIKEN	Tanker	249	43	8	60.14215	27.66357	58.31898	20.5882	243.182544	22.583333	10.7682
4 03 2018 18:06	5 03 2018 17:12	9274630	MAERSK EDGAR	Tanker	186	31	7	60.11783	27.57617	58.328	20.618	239.118069	23.1	10.3514
3 03 2018 17:15	4 03 2018 00:53	9380415	DUZGIT INTEGRITY	Tanker	131	19	8	60.30721	25.55378	59.52599	24.50649	56.513027	7.6333333	7.40345

Fig. 3. The processed AIS data with information on ship voyages required for simulation and analysis, e.g., coordinates of the start and end points, time of departure and arrival, and IMO number and basic technical information on the ship.

The second layer of the information structure of the model—the Engineering database—contains the technical data to model the performance of traffic ships and icebreakers, e.g., speed, energy consumption, and environmental performance of a ship. Figure 4 shows a fragment of the technical data on ships used for the simulation. The data for each ship contains information on the total maximum power of the power plant, installed propulsion power, ship power transmission, the type of the main engine, the type of fuel, hotel load of a ship, specific fuel consumption, and the ID of the corresponding h-v curve (hvcode). The h-v curve shows the maximum attainable speed of a ship in the ice of a particular equivalent ice thickness for a specific power output [16]. For further details on the applied methodology for calculating ship speed in ice using h-v curves, see [9]. The energy consumption and emissions are calculated according to the methodology presented in [8].

The third data layer—Space and Environment—contains information on the studied sea area, e.g., coordinates, icebreaking zones, location of the ports, and spatial and

IMO	ME kW	Max prop.	Transmition	Engine	Fuel type	Hotel load	SFC(@100%MCR)	Name	hvcode
9350783	3840	3840	Shaft	Medium-speed	Diesel	272	177	Aland	0
8821814	4950	4950	Shaft	Medium-speed	Diesel	422	185	Amstelgracht	1
9228980	5440	5440	Shaft	Medium-speed	Diesel	529	183	Arctica-1	2
8202381	8052	8052	Shaft	Low-speed	Diesel	589	170	Asian Breeze	3
9121998	14480	14480	Shaft	Medium-speed	Diesel	657	175	Auto Baltic	4
9190157	9840	9840	Shaft	Medium-speed	Diesel	568	185	Autoprestige	5
9260029	9488	9488	Shaft	Low-speed	Diesel	554	175	Baltic Champion	6
9267716	9450	9450	Shaft	Medium-speed	Diesel	602	185	Balticbord	7
9313228	12640	12640	Shaft	Low-speed	Diesel	1519	175	Barmbek	8
8820860	5920	5920	Shaft	Medium-speed	Diesel	416	185	Birka Exporter	9
8405880	21840	15000	Diesel-electric	Medium-speed	Diesel	680	185	ZZ_OTSO	10
9734161	21000	19000	Diesel-electric	Medium-speed	Diesel	671	185	ZZ_POLARIS	11
7347615	17100	16200	Diesel-electric	Medium-speed	Diesel	642	175	ZZ_URHO	12
9832119	2010	2010	Shaft	Medium-speed	Diesel	179	173	Honfleur	13

Fig. 4. The fragment of the technical data on the traffic ships and icebreakers used for simulation.

temporal ice data. The studied sea area is divided into icebreaking zones, typically based on the severity of the ice condition. One or more icebreakers are usually assigned to a specific icebreaking zone. The ice data is sourced from the ice charts of the Finnish Meteorological Institute (FMI) database [17]. The ice charts are produced by processing the satellite imagery and contain information on the parameters like ice thickness and concentration. For example, Fig. 5 shows the satellite imagery and the corresponding FMI ice chart for the ice conditions in the Bothnian Bay on Jan 8, 2024. Using h-v curves for modeling ship performance requires that ice data is provided as one integral value—the equivalent ice thickness, which is calculated as a function of the ice thickness and concentration using the method described in [9].

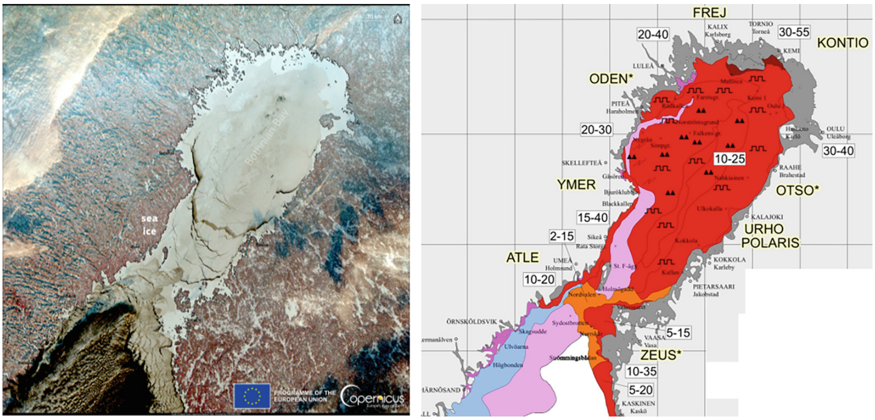

Fig. 5. The satellite image (European Union, Copernicus Sentinel-3 imagery) and the corresponding FMI ice chart [17] for the ice conditions in the Bothnian Bay on Jan 8, 2024.

When all data layers are ready, the simulation reproduces time-sorted voyages starting from those with the earliest departure time. The ship sails independently from the departure port to the destination port following the dirways. The performance of a ship corresponds to its technical characteristics, acquired from the database according to its ID, considering specific ice conditions specified in the GIS database for a particular date and coordinates. If the ship speed drops below a specific threshold defined by the user, it is considered stuck and sends a service request to an icebreaker assigned to the actual icebreaking zone. Each icebreaker keeps a list of requests and assists the stuck vessels based on the first-in-first-out principle. Figure 6 shows the progression of the simulation experiment with the dynamics of the ship traffic (the brown ships), ice conditions, and icebreaking assistance performance (the grey ships) for a virtual period from Jan 15 to Feb 17, 2018. The equivalent ice thickness is shown in Fig. 6, where the lightest blue represents the most favorable ice conditions, and the darkest blue shows the thickest ice. The key performance indicators of the WNS are tracked for any modeling moment.

3 Discussion of the Model and Its Applications

The developed tool for the simulation of the Baltic WNS has been successfully applied from 2022 to 2025 in four different research projects. The first pilot application of the tool for modeling the WNS in the Bay of Bothnia demonstrated its significant advantages over existing approaches and proved it highly promising for conceptual design and analysis of the Baltic WNSs [10]. The efficiency of the icebreaker assistance is measured using the total waiting time—the accumulated total time of all traffic ships spent waiting for icebreaker assistance. For example, Fig. 6 shows the part of the WNS model interface with histograms for the total waiting time specified for the specific ports and the value accumulated for the entire system.

Another study proposed a novel formulation and verification of the ship performance model for the simulation of the Baltic WNS, significantly improving the quality of the ship performance predictions for more complex ice conditions, power variation, and icebreaker assistance [9]. A more efficient data-mining method for preparing the AIS data for the Baltic WNS is proposed in the study [18].

The model is further advanced in the study [8], where two new performance indicators—the total CO_2 emissions and the total cost of the WNS operation, measured as the total sum of the corresponding values for the traffic ships and the icebreakers– are proposed. Introducing new functionality allows for a multi-objective analysis of the WNS, where the technical performance, sustainability, and cost-efficiency are studied. The preliminary tests showed the capacity of the approach to provide up to 7% CO_2 emissions reduction and up to 14.2% cost reduction compared to the basic scenario modeling real-life conditions in the average winter. The reductions have been achieved by changing the WNS parameters—the number, technical characteristics, and location of icebreakers, the share of propulsion power used by traffic ships, and the threshold speed below which the icebreaker assistance is requested. The basic scenario was developed in collaboration with the Finnish Transport Infrastructure Agency representatives[8].

Another work [13] applied the simulation tool for a new region to study the WNS in the Estonian part of the Gulf of Finland and the Gulf of Riga. The authors collected, processed, and verified the new data on the ship traffic, shipping routes, ice conditions, and the icebreaker fleet. Besides, the different scenarios for future ice conditions are considered, allowing for analysis of the effect of a warming climate in future winter navigation. The study demonstrated significant flexibility of the developed tool—it can be efficiently applied to simulate different Baltic WNS with limited modifications and data preparation, which could be done in a reasonable time.

The simulation experiment presented in Fig. 6 shows that the developed decision-support tool can effectively model the dynamics of ship operation in ice conditions, capturing the complex behavior of traffic ships and icebreakers. Figure 6 shows the progression of the WNS operation—the first snapshot indicates the initial state of the system where all ships are at their home ports, followed by the snapshots showing how ships chronologically execute their voyages. As the model progresses, more ships are stuck and ask for icebreaker assistance, making all icebreakers busy in the last snapshot.

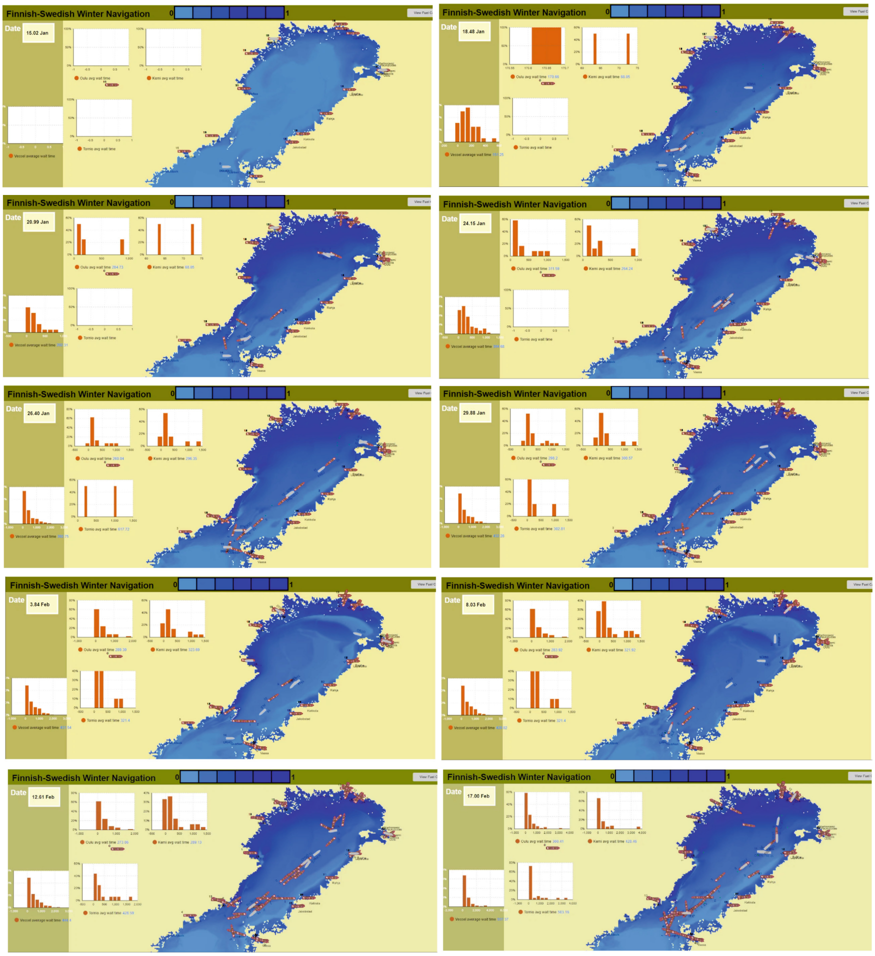

Fig. 6. The progression of the simulation experiment shows the dynamics of the ship traffic (the brown ships), ice conditions, and icebreaking assistance performance (the grey ships) for a virtual period from Jan 15 to Feb 17, 2018. Light blue represents the most favorable ice conditions, and dark blue shows the thickest ice.

The future application of the developed tool is highly promising, specifically what-if analysis for different regions of operation, scenarios of traffic and ice conditions, various configurations of icebreaking fleets, and their operational tactics. Although the current version of the tool is designed and verified for the Baltic WNS specifics, it has a high potential to be modified for the efficient simulation of polar WNS.

Future research can address the limitations of the proposed tool, namely,

- provide a more advanced representation of the ice conditions by improving the methodology of the equivalent ice thickness to consider more ice properties;
- Improve the ship performance model for a more detailed simulation of ship performance (speed, fuel consumption, and emissions) in ice with a specific equivalent ice thickness;
- Advance the logic of the icebreaking assistance in the model, making it closer to the complex real-life decision-making;
- Extend the functionality of the tool to study how the future development of offshore wind farms will affect ice conditions, ship traffic, icebreaking assistance, and the integral performance of the WNS;
- Improve the ice routing capabilities of the model, e.g., by automatically creating the dirways considering relevant ice conditions;
- Provide more integration with existing GIS tools, e.g., automatic reading of the coastlines to prevent the ships from occasionally crossing the land.

4 Conclusions

The complexities of ice navigation are significant and incredibly uncertain, especially considering the rapidly changing climate and increasing interest of the maritime industry in operating in new, colder regions. Independent handling of them by individual ships, shipping companies, or even countries is challenging without a systemic approach. In this paper, we provided an overview of the functionality and applications of our comprehensive simulation tool for systemic analysis of different aspects of the winter navigation systems, contributing to efficient and sustainable shipping in cold regions. The tool has been successfully applied to different Baltic winter navigation systems, considering the ice conditions, the technical parameters of ships in the traffic, parameters of ship voyages, established maritime routes in the region, and supporting infrastructure (e.g., availability and technical parameters of icebreakers, icebreaking assistance, and ice routing provided by the authorities).

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