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SIMNAV: AI-BASED SIMULATION FOR INTELLIGENT ICE NAVIGATION

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FOREWORD

In this report no 124, the Winter Navigation Research Board presents the results of research project SIMNAV: AI-based simulation for intelligent ice navigation. The project implemented AI-based tools to simulate different operational traffic parameters of winter navigation. Created model was verified against real historical data.

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SIMNAV: AI-based simulation for intelligent ice navigation

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Final report

This article summarizes the work done towards the SIMNAV project from January 2022 till September 2022. The overall objectives of the project as stated in the proposal are as follows.

Project objectives:

1. Integration of operational level details of ships, ice characteristics and system level details such as traffic flows and icebreaker scheduling
2. Modelling of convoys and towing arrangements
3. Using intelligent techniques along with AIS and ice forecast data to estimate the parameters which cannot be accounted for via physics-based approaches.

The primary aim of this project was to develop an advanced simulation tool for the analysis of the FSWNS. The functionalities of the model are parameterized, where users can vary convoy sizes, speed limit thresholds and ice conditions to study their impacts on system level traffic.

<u>Changes to initial plan</u>

Since the scope of the project was reduced from 1 year to 3 months, the extent of research into AI techniques has been greatly reduced. The project focused on making the simulation tool robust, reliable, and user-friendly, while using different intelligent techniques for parameter validation. The objectives addressed are now described in more detail.

<u>Simulation modelling: integration of the operational and system-level details</u>

The simulation tool is implemented using a combination of discrete-event and agent-based simulation along with process flow modelling. This choice of modelling techniques allows for the visualization of the simulation processes and results and incorporation of stochastic elements. The behavior of individual entities of the FSWNS, such as individual merchant vessels, icebreakers, and ports, are modelled using an agent-based framework, including details of their decision-making logic. Each entity (vessel or icebreaker), has several decisions to make during the winter, reacting to the changing parameters. The decision-making logic for each entity involves a set of rules in the if-then-else format, where entities change their speed, direction and mode of operation based on system parameter values. The traffic data used in the model has been obtained through the research project WINMOS II. It includes information about origin and destination ports, arrival, departure, and time spent at the port, vessel name and type (for hv curve) and the next destination. The vessel itineraries used in the model are a result of AIS data processing work. Based on this work, it possible to know whether a ship is at port or sea. Figure 1 shows the way the operational and system-level information is added to the tool. Ice channels and drift are currently not included in the model, but the framework is built to enable their smooth incorporation in the future versions.

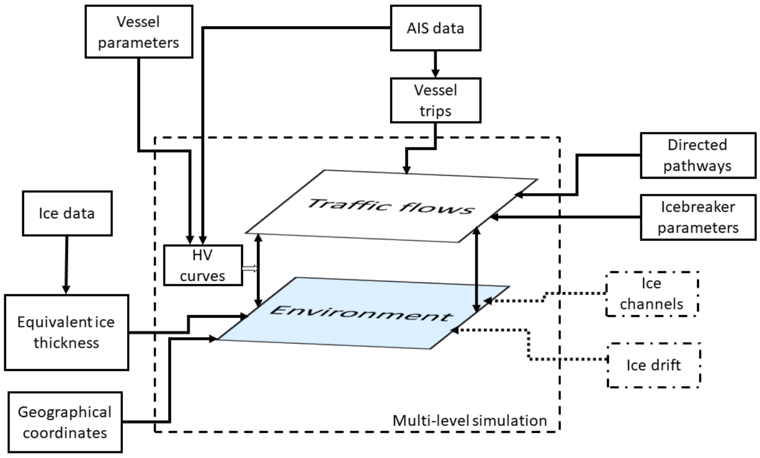

Figure 1: Schematic of integrated tool

To effectively capture the challenges of navigation, it is important to model the ice conditions appropriately. The information is available through ice charts published by the Finnish Meteorological Institute (FMI). The ice data is also highly dynamic and new ice information is available for each hour of each day, for every square mile of geographical area. For use in this model, this information is suitably aggregated, to ensure an acceptable compromise between the level of detail and the model computational time. The vessels modeled in the simulation need to be sensitive to these ice changes and adapt their speeds (or stop) in response to the conditions. This requires a mechanism for the vessels to monitor ice parameters and evaluate their response several times during a single trip. for calculating the equivalent ice thickness. The HV curves are a polynomial regression that describes the variation of speed of vessel as a function of ice thickness. Each vessel has an HV curve profile, based on its dimensions. The HV curves are modeled as entity attributes, and they evaluate the changing speeds based on the equivalent ice thickness values.

Implementation: modelling special arrangements (convoys) and parameterization

The simulation component of the tool is a standalone model developed using Anylogic® software. The model is an agent-based, discrete-event simulator with specific add-on functionalities coded using Java. The simulation provides a unified platform to integrate agents, their environments, process flows and system uncertainties (stochastic elements). The purpose of the simulator is to mimic the operations of the FSWNS, considering all relevant underlying performance factors and attributes of the system. This tool helps compare alternative navigational scenarios to finally arrive at the most efficient combination of policies and actions.

The environment includes varying ice conditions over the winter period. Based on ice data from FMI, the ice thickness and topography can change for every mile of the sea area and as often as every day, during the winter months. The paths that the vessels follow, known as dirways, are also a part of the environment. Dirways are created by icebreakers where there is ice and are subject to change due to wind, pressure and changing ice conditions. This dynamically changing input data is modelled as events in the simulation. When an event occurs (change in ice data or dirways), all agents are notified, and their operations are suitably modified. Another aspect that needs to be captured is the transition between dirways. The ongoing journeys are completed on the old dirways and the new journeys are scheduled on the new dirways. Icebreakers need to coordinate between both set of dirways until all traffic is smoothly flowing on new dirways. This affects convoy formation as well. All these changes can affect the waiting time of the system. The speed of vessels, however, depends primarily on the ice conditions they encounter.

The entire operational area is divided into operating zones. These zones are defined based on ice conditions and can change dynamically over the course of a simulation run. At least one icebreaker is available in each zone. Icebreakers have specific ice-going capabilities that are modelled using hv curves. The assignment of an icebreaker to an operating zone depends on the maximum ice thickness in the region and the capabilities of the icebreaker. It is usually the practice that wider and stronger icebreakers are assigned to the northern regions more frequently, which are frozen sooner and for longer duration. The ice thickness is also greater in these parts and more ridging is common. Apart from ice conditions, the other factor affecting the choice of number of icebreakers is the expected traffic density in the area. Some ports are busier than the others, even during peak winters. Excessive queue build-up needs to be avoided in the areas surrounding these ports and along pathways leading to these ports. It is assumed that 4 icebreakers are available for the Finnish ports at any given time.

Although icebreakers are assigned to zones, they regularly coordinate with each other to ensure that the entire system operates safely and efficiently. Vessels often need assistance across multiple icebreaker zones. Typically, each icebreaker guides the vessel through its operating zone, leaving it at a safe stopping point called waypoint. At the waypoint, the next icebreaker takes over the assistance mission and guides the vessel further along its navigational journey. Icebreakers can, however, operate outside their operating zones to ease out building traffic or to help larger vessels that need 2 icebreakers.

For the time period under study (15 Jan-15Feb 2018), 199 vessels have been found to operate in the Bay of Bothnia (region of interest). These have been categorized into 44 ship types, based on their dimensions. Every ship type corresponds to a set of hv coefficients. There are different coefficients for level ice, open waters, and when assisted by an icebreaker. The hv curve expressions are sensitive to ice thickness variation. There are several parameters included in the model that can be controlled by the user. These allow for testing what-if scenarios. Table 6 shows the key parameters of the models that are varied for performing different runs of the simulation.

Table 1: Range of parameters

Parameter	Range	Default
Vessels in system (V)	1, 25, 50, 100, 116	116
Vessel speed threshold (s_v)	(3, 6) KN	3KN
Maximum allowable waiting time (t_{max})	(12, 24) hours	12 hours
Convoys allowed (C_{on})	0, 1	1
Maximum convoy size (C_{max})	(2, 6)	2
Minimum convoy speed (s_c)	(6, 8) KN	6KN

Icebreakers often try to combine trips of multiple vessels requiring assistance, so that the waiting time is reduced overall. When a single icebreaker assists more than one vessel, the arrangement is known as a convoy. There are multiple factors in deciding how many vessels can be a part of the convoy. The convoy travels at the speed of the slowest vessel. Hence the icebreaker needs to ensure that the minimum speed of convoy is greater than the threshold. If the speed of convoy is less than “x” knots (default is 6), then the slowest vehicle is left behind. In practice, the slowest vessel may be taken up for towing by the icebreaker and the rest of the vessels follow in a convoy. However, this case is not considered in the current model. The current model considers conventional convoys with one icebreaker clearing a path for one or more merchant vessels. While forming a convoy, the travel paths of the vessels are also considered. An icebreaker leading a convoy does not escort each individual vessel to its destination ports. Safe waypoints are identified where convoys can be dismantled and reformed if required with different vessels. It is possible that due to convoy formations one or more vessels end up taking a longer route to their destinations. However, keeping in mind the overall waiting time in the system, the longer route with convoys ends up being more efficient. The logic of convoy formation has been implemented and demonstrated (on 25th May 2022). Icebreakers operate in assigned zones. When an icebreaker receives multiple requests for assistance at the same time, it prioritizes vessels based on the "longest waiting time first" principle. Then, once the icebreaker reaches this chosen vessel, it scans the nearby area (10km or other chosen parameter) to check for any other vessels requiring assistance. Convoys are formed if other vessels headed in similar directions are found in the vicinity.

<u>Validation studies</u>

The historical data contains arrival and departure time at ports, along with the time spent at the port. The port departure times are included as input in the model. The arrival of the vessel at its destination port depends on the ice conditions, dirways, availability of icebreakers and the logic of how icebreakers prioritize assistance requests from multiple vessels. One of the ways to validate the model is by comparing the arrival times of vessels at different ports in its schedule with the historical arrival times. A total of 249 trips were analyzed. For ease of visibility, a set of ships were chosen to be presented. Figures 8A and 8B show the simulated and historical arrival times plotted for two sets of ships. It is observed that most trips are close to their expected arrival times. There are instances, such as Vessel 4 in Figure 8B, where significant delays are experienced. Study of such cases will help to improve the model in the future work.

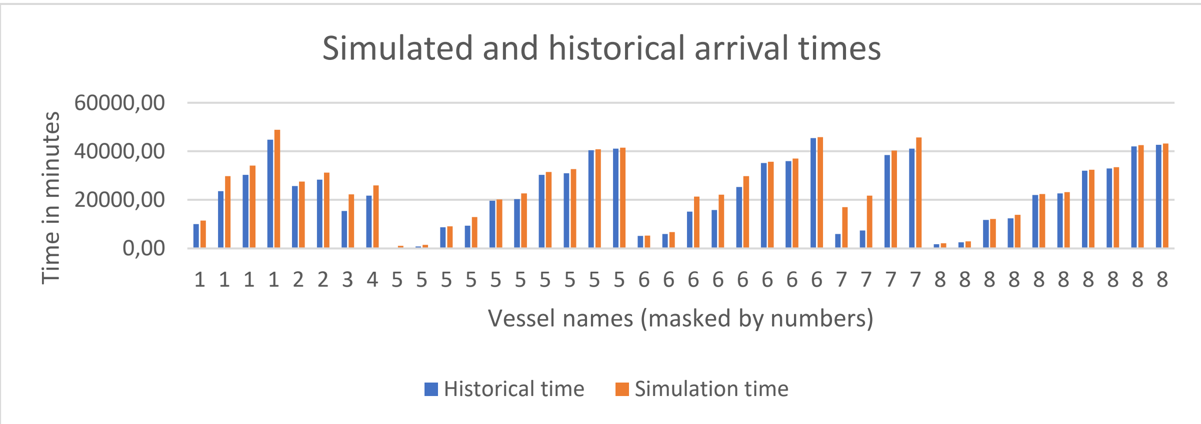

Figure 8A: Historical and simulated arrival times comparison- Set 1

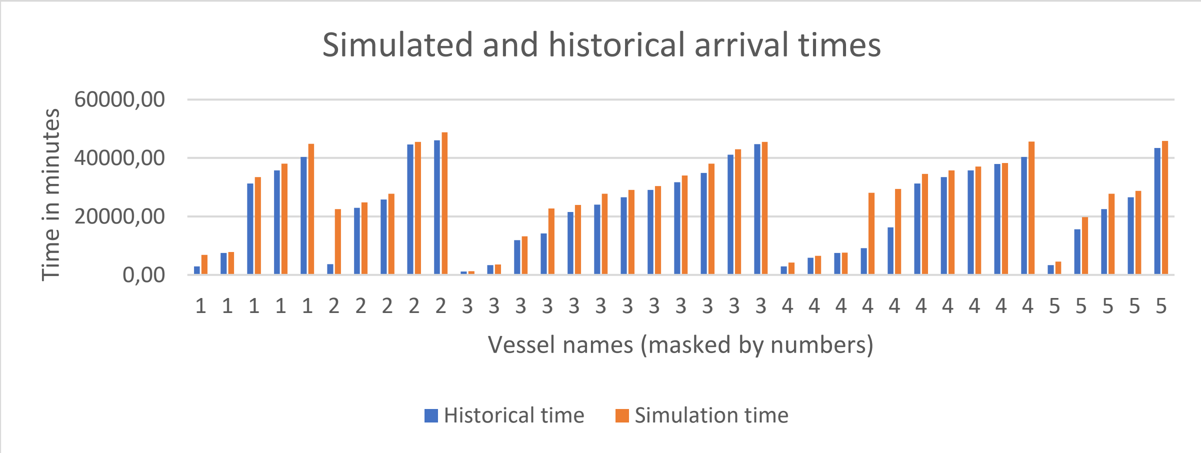

Figure 8B: Historical and simulated arrival times comparison- Set 2

Ship performance calculation in the simulation tool is based on hv curves and equivalent ice thickness. The hv curve of a sample ship which has the most similarity to a candidate ship is used as the hv curve of the candidate ship. The equivalent ice thickness denotes the average ice thickness in a grid. In addition, the MCR change is considered by a scaling approach based on the actual power and full power. A validation study has been carried out to check how well the ship performance calculation method can predict real ship voyage. An example is given in Figure 2. The validation indicates that the method can give realistic estimation of real ship voyage.

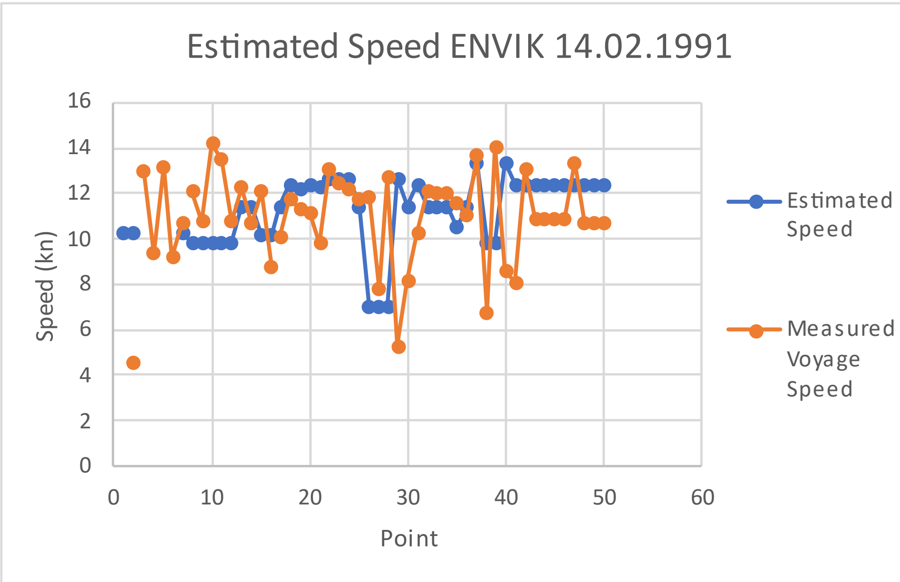

Figure 2. Comparison between estimated and record speed variation in a voyage.

Summary of work done and possible future research

A simulation tool is implemented that presents a powerful visualization and integration of data from different sources into a unified, functional model. The model captures varying ice conditions in detail and their impact on vessel speeds and dirways. Icebreaker assistance is modelled including convoy situations. The model is based on real world historical data and inputs from field experts. The behavior of vessels and icebreakers is defined through agent-based simulation paradigm to capture these effects. The model has been validated, both by visual inspection and by comparison with historical data. The results indicate that the model is in close agreement with the conceptual description and with the historical data. Navigation of merchant vessels in ice and their interaction with icebreakers has many complexities involved. Through multiple experiments, some of these complexities were identified and studied.

The report has discussed how the three objectives have been worked on in this project. The model will be further developed and applied to additional scenarios and continuously validated against historical data. Test cases will be built to check for consistency with actual observed behavior of vessels and icebreakers. The schedules of individual vessels will be cross verified along with their speeds at random instances of time. Data management for the FSWNS system is a large and complex project. The work done so far is a step in the direction of building an integrated database management system which can assimilate information from diverse sources in a seamless manner. As part of future research, the model fidelity can be worked on, with greater focus on ship level details and more detailed ice information such as pressure and topography. More case studies can be developed to test the effect of ship level details on system performance.

Manuscripts published:

- Kulkarni, K.; Kujala, P.; Musharraf, M.; Rainio, I. Simulation Tool for Winter Navigation Decision Support in the Baltic Sea. Applied Sciences. 2022, 12, 7568. https://doi.org/10.3390/app12157568
- Kulkarni, K.; Li, F.; Liu, C.; Musharraf, M.; Kujala, P. System-level simulation of maritime traffic in northern Baltic Sea. Proceedings of the Winter Simulation Conference Dec. 2022.