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Martin Bergström and Pentti Kujala

HOLISTIC SIMULATION-BASED ASSESSMENT OF THE OPERATIONAL PERFORMANCE OF THE FINNISH-SWEDISH WINTER NAVIGATION SYSTEM

Finnish Transport and Communications Agency

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FOREWORD

In this report no 112, the Winter Navigation Research Board presents the results of the study simulation-based approach for assessing the operating performance of the Finnish-Swedish Winter Navigation System (FSWNS) under different operating scenarios. The operating performance is assessed with such indicators such as transport capacity, the number of icebreaker assistance and icebreaker waiting times.

The study may provide new insights into the behaviour and performance of the FSWNS under different operating scenarios.

The Winter Navigation Research Board warmly thanks Mr. Martin Bergström and Mr. Pentti Kujala for this report.

Helsinki and Norrköping

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Project number: W18-1 SimWinNS

Executive summary

This report presents a simulation-based approach for assessing the operating performance of the Finnish-Swedish Winter Navigation System (FSWNS) under different operating scenarios. The operating performance of the system is assessed in terms of performance indicators such as transport capacity, the number of instances of icebreaker (IB) assistance, and IB waiting times. Different operating scenarios are specified in terms of ice conditions, the volume of maritime traffic, number of IBs, and regulations such as the Energy Efficiency Design Index (EEDI).

The presented approach is based on the technique of discrete event simulation (DES). This means that the behaviour of the simulated system is modelled as an ordered sequence of events, each of which takes place at a specific point of time and results in a change in the state of the system. Because no change occurs between events, this enables fast simulations of extensive operating periods.

Due to various knowledge gaps, as well as due to technical limitations of the applied simulation technique, the approach relies on generalized assumptions about the operations of the FSWNS. For instance, vessels are assumed to operate along predetermined routes, IBs are assumed to assist vessels one by one, and generalized assumptions are made about the criteria for receiving IB assistance as well as the presence of ice channels. As a result, the approach appears best suited for scenario-based assessments in which the performance of the FSWNS is assessed for a limited period (e.g. one month) with relatively heavy ice conditions during which the shipping routes or ice channels can be assumed constant.

The approach is validated against real-life data on maritime traffic in the Bothnian Bay in the period 15.01-15.02.2010. In terms of the number of ship arrivals per port, representing the transport capacity of the FSWNS, the simulation agrees well with the data. However, in terms of the number of instances of IB assistance and IB waiting times, the deviation between the simulation and the data is significant with standard deviations of 11 % and 22 %, respectively. This indicates that the approach is mainly suited for rough scenario-based assessments to determine whether the capacity of the FSWNS under the simulated conditions is sufficient to keep the system in 'balance'.

A case study is carried out for a future scenario in which around one third (33 %) of the present fleet of merchant ships entering the Bay of Bothnia is replaced by EEDI compliant ships. The case study indicates that the considered EEDI scenario would, in comparison with the default scenario, increase the total number of cases of IB assistance from 225 to 328 (+46%) as well as increase the average waiting times for IB assistance from 4.0 hours to 6.9 hours (+73%). The case study also indicates that the predicted increase in IB waiting times can be mitigated if the number of IBs operating in the area is increased from 4 to 5. However, due to a lack of detailed data on how the EEDI would affect the attainable speed in ice of individual ships, the outcome of the analysis is not conclusive.

In summary, the presented approach may provide new insights into the behaviour and performance of the FSWNS under different operating scenarios. A strength of the approach is that it in principle allows quick analysis of multiple different operating scenarios, e.g. with regards to ice conditions, traffic volumes, IB availability, and regulations such as the EEDI. Notwithstanding, for improved accuracy and reliability of the approach, additional research and development are needed.

Acknowledgements

The authors gratefully acknowledge the funding by the Winter Navigation Research Board. We would also like to thank the many organizations and individuals who provided guidance and support throughout this study. Special thanks to Mr. Morten Lindeberg for providing valuable input data.

Contents

Nomenclature

Abbreviations

AMTS	Arctic maritime transport systems
DES	Discrete event simulation
DWT	Deadweight tonnage
EEDI	Energy efficiency design index
FSICR	Finnish-Swedish ice class rules
FSWNS	Finnish-Swedish winter navigation system
GHGs	Green House Gasses
IB	Icebreaker
IMO	International Maritime Organization
MCR	Maximum continuous rating
PDF	Probability density function
PTT	Port turnaround time
SFC	Specific fuel consumption

Symbols

C_F	Amount of CO2 per gram of fuel (3.1144 g)
C_{max}	Maximum ice concentration
L	Navigation leg
H_{eq}	Equivalent ice thickness
H_{eq_avg}	Average equivalent ice thickness
H_{eq_max}	Maximum equivalent ice thickness
H_{max}	Maximum ice thickness
H_{min}	Minimum ice thickness
$H_{Ridging\_avg}$	Average equivalent ice thickness caused by ice ridging
$H_{Ridging\_max}$	Maximum equivalent ice thickness caused by ice ridging
v	Speed in knots

1 Introduction

The Baltic Sea is an important transit route connecting numerous countries and markets. In 2019, the total volume of Finnish import and export transported over the Baltic Sea exceeded 100 million tons, corresponding to around 80 percent of the total trade (Finnish shipowners association, 2020) (Meriliitto, 2020). These numbers are expected to increase as the long-term trend in the volume of Finnish seaborne trade is one of growth (Traficom, 2018).

As per Figure 1, in winter large parts of the Baltic Sea are typically ice-covered, but with significant interannual variability with regards to the maximum ice extent. Because the presence of sea ice has a significant impact on the operations and transit times of ships, the varying sea ice cover presents a challenge to the planning of maritime operations in the region.

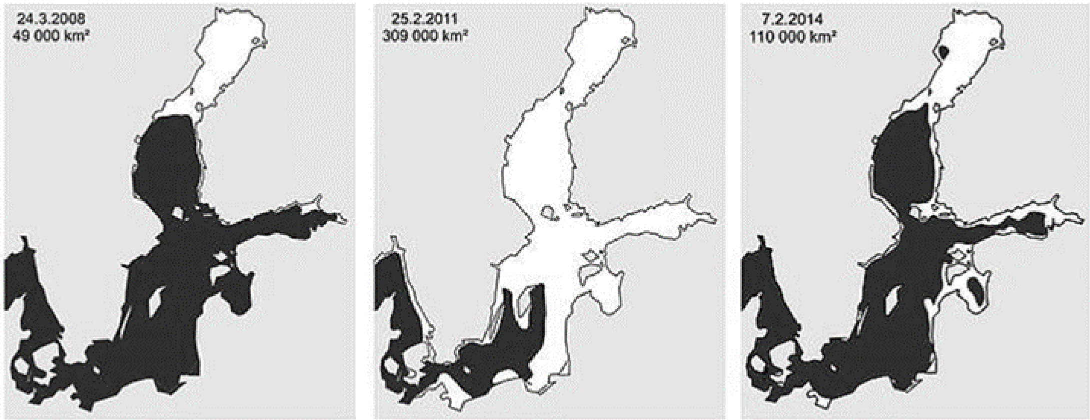

Figure 1: The maximum ice extent for three different winters (FMI, 2019).

The aim of the Finnish-Swedish Winter Navigation System (FSWNS) is to maintain safe and efficient year-round navigation to and from Finnish and Swedish ports along the Baltic Sea (Traficom, 2017). To this end, the FSWNS manages winter navigation-related challenges by the combined use of (a) ice class rules, (b) traffic regulations, and (c) icebreaker (IB) assistance (Jalonen, et al., 2005). Specifically, to make sure that ships have enough ice-going capability for safe and efficient operations, they must be built and operated following the Finnish-Swedish Ice Class Rules (FSICR) (TRAFICOM, 2017). These are enforced by port-specific traffic restrictions set by Finnish and Swedish maritime authorities in terms of the minimum ice class and deadweight needed to be eligible for IB assistance (Traficom, 2017). IB assistance is provided based on the available fleet of Finnish and Swedish state-owned and operated IBs. As per Arctia (2019) and (Sjöfartsverket, 2019), Finland has a fleet of 8 major IBs (Polaris, Fennica, Nordica, Otso, Kontio, Voima, Sisu, and Urho), whereas Sweden has a fleet of 5 major IBs (Ale, Atle, Frej, Oden, and Ymer).

Both in the short- and longer-term, the performance of the FSWNS is expected to be influenced by the International Maritime Organization's (IMO) Energy Efficiency Design Index (EEDI) regulations. These regulations, which were adopted by the IMO in July 2011, aim to reduce the amount of Green House Gasses (GHGs) from ships by promoting the use of more energy-efficient solutions (IMO, 2018a). Anyhow, due to the technical content of the regulations, they are expected to limit the installed propulsion power of ships, which reduce their ice-going capability and attainable speed in ice. This in turn could increase the demand for IB assistance, resulting in longer waiting times for IB assistance, and hence increase the overall transport costs and time.

Towards assessing the effects of the EEDI, and to identify and assess possible mitigation measures, this report presents an approach for assessing the operational performance of the FSWNS under various operating condition scenarios. To deal with the complexity of the system, the presented approach is based on a simulation-based approach for the conceptual design of Arctic maritime transport systems (AMTS) presented by Bergström (2017). This approach has been proven well suited to assess the performance of a winter navigation transport system consisting of a fleet of ships operating between two ports, with or without IB assistance. In this study, the approach is extended to deal with the complexity of the FSWNS.

The remainder of this report is structured as follows: Ch. 2 presents concepts and regulations related to the study, Ch. 3 presents the working principles of the proposed simulation-based approach, Ch. 4 presents a validation of the approach, Ch. 5 presents a case study of how the approach can be applied to assess the impact of the EEDI, and Ch. 6 summarises the outcome of the study and discusses potential future developments.

2 Background

2.1 Finnish-Swedish ice classes and IB waiting time

The aim of the Finnish-Swedish Ice Class Rules (FSICR) is to ensure that ships engaged in trade in the Northern Baltic Sea have enough ice-going capability to maintain safe and efficient navigation year-round to and from Finnish and Swedish ports (Traficom, 2019). To this end, the rules, which have been developed jointly by the Finnish and Swedish maritime authorities based on accumulated experience and research, specify five ice classes: IA Super, IA, IB, IC, and II. Enforcement is through port-specific restrictions determining the minimum ice class and deadweight needed to be eligible for IB assistance (Traficom, 2019).

The demand for IB assistance in a region depends among others on the prevailing ice conditions, the amount of maritime traffic, and the ice-going capability of the ships operating there. If the demand for IB assistance exceeds the available icebreaking resources, ships' waiting time for IB assistance will increase. To maintain smooth and efficient maritime traffic, the goal of the Finnish IB service is to limit the average waiting time to 4 hours (BIM, 2015). To this end, the FSICR places ice class-specific performance requirements on ships. These are determined as per Table 1 in terms of the minimum ice conditions in which a ship must be able to maintain a speed of at least 5 knots (Traficom, 2017).

Table 1: Ice class-specific minimum ice conditions in which a ship must be able to maintain a speed of at least 5 knots (Traficom, 2017).

Ice class	Minimum ice conditions
1A Super	1.0 m thick brash ice with a 0.1 m thick consolidated layer of ice
1A	1.0 m thick brash ice
1B	0.8 m thick brash ice
1C	0.6 m thick brash ice

2.2 Energy efficiency design index (EEDI)

The EEDI regulations regulate a ship´s CO_2 emissions by specifying its maximum allowed EEDI value determined as a function of DWT or gross tonnage (GT) separately for different types of ships (e.g. bulk carriers, tankers, gas carriers, ro-ro cargo ships) (IMO, 2018b). As per Figure 2, the maximum allowed EEDI will be tightened incrementally every five years (IMO, 2018a).

In simplified terms, a ship's EEDI value represents the amount of CO_2 generated by the ship while doing a specific transport work (IMO, 2018b). Accordingly, the EEDI value can be expressed as per Eq. 1 based on engine power, specific fuel consumption (SFC), an assumed amount of CO_2 per g of fuel (C_F), deadweight tonnage (DWT), and ship speed (IMO, 2016).

$$EEDI = \frac{CO_2\ emissions}{transport\ work} = \frac{Engine\ power * SFC * C_F}{DWT * speed} \qquad (1)$$

As per Eq. 1, for a given type of engine and fuel, the EEDI regulations effectively limit the maximum installed propulsion power. Therefore, to make ice-class ships comparable with open water ships, considering their higher propulsion power needed for a sufficient ice-going capability, the EEDI regulations include correction factors for such ships (Kämäräinen, 2017). These are determined for five different types of ships: tanker, bulk, general cargo, container, gas carriers, and Ro-Ro ships (Kämäräinen, 2017). Notwithstanding, the EEDI regulations are expected to reduce the average propulsion power, and consequently also the average ice-going capability of ice classed ships. A reduced ice-going capability of a ship implies both a lower threshold in terms of the maximum ice conditions in which the ship can operate independently and lower speed in ice. For a given sea ice scenario, this will increase both the number of instances where a ship needs IB assistance and the duration of each instance of IB assistance. As a result, the demand for IB assistance is expected to increase (Prime Minister´s Office, 2017). Additionally, considering the maritime industry's overall efforts to optimize maritime operations, the demand for IB assistance might also be driven by other than EEDI related cost and energy consumption reducing measures, reducing the average ice-going capability of ships.

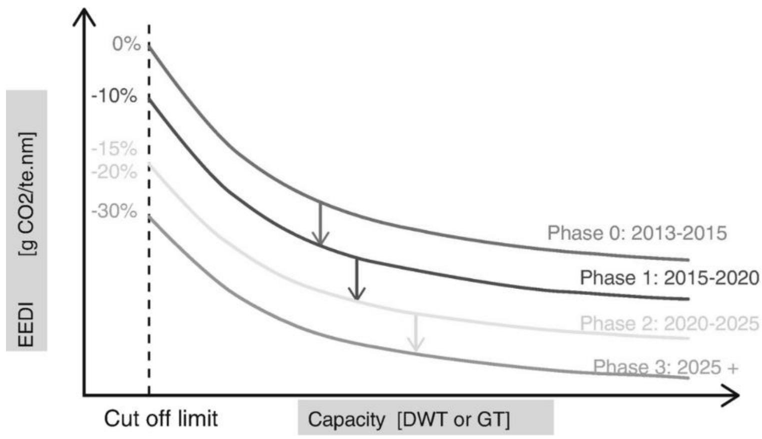

Figure 2: Concept of required EEDI, reduction factor, cut-off limits, and EEDI phase (IMO, 2016).

3 Description of the simulation model

3.1 Discrete event simulation

The presented simulation approach makes use of system thinking and the technique of discrete event simulation (DES). DES is a specific type of simulation in which the behaviour of a system is modelled as an ordered sequence of events, each of which takes place at a specific point of time and results in a change in the state of the system (Craig , 1996). Because no change occurs between events, DES enables fast simulations of extensive operating periods. Bergström (2017) demonstrated that for Arctic maritime transport systems, DES can consider a wide range of uncertain and stochastic parameters, as well as various interaction and self-reinforcing effects, and to assess how these affect the system's transport capacity and IB waiting times, among other performance indicators.

3.2 Model structure

As per Figure 3, the simulation model consists of different types of blocks representing navigation legs (L), ports, crossings, borders between different IB operating areas, and ship entry/exit gates. Ships are represented by entities, each of which has a set of predetermined attributes specifying the technical characteristics and route of the represented ship. Each ship entity enters the simulation model at a specific time through an entry gate with an assumed geographical location (e.g. Kvarken, Bay of Bothnia). Once entered, a ship entity will progress towards its first port of destination, where it will stay for a predetermined period corresponding to the total port turnaround time. Thereafter the ship entity will either continue towards another port within the simulation model, or towards a port located outside the simulation model. In the latter case, the ship entity will progress towards an exit gate with an assumed geographical location and then leave the simulation model.

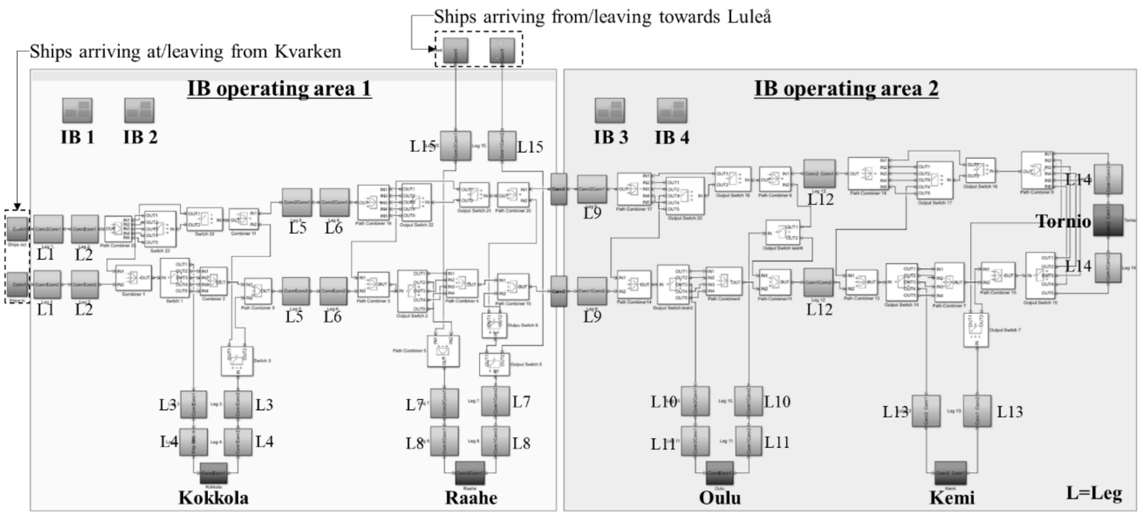

Figure 3: Simulation model example

Navigation legs are here defined as the geographical distance between two waypoints. The time it takes for a ship entity to complete a leg depends on the leg distance, the ice conditions, the operating mode (independent or assisted operation), the ship's estimated speed in the prevailing ice conditions and operating mode, and the waiting time for IB assistance (in case the ship must call for IB assistance). Specifically, navigation legs are modelled as per the schematic diagram in Figure 4 whose various elements are described as follows:

A. **Date definition.** When a ship entity (with or without IB assistance) arrives at a waypoint, the present date is determined based on the assumed start date of the simulation and the elapsed time since the start.

B. **Ice conditions.** The prevailing ice conditions are determined following a predefined table defining the ice conditions by navigation leg and date. Also, based on the location and prevailing ice conditions, an assumption is made as to whether a brash ice channel is present. The prevailing ice thickness along the leg is defined in terms of the average equivalent ice thickness (H_{eq_avg}) and the maximum equivalent ice thickness (H_{eq_max}). H_{eq_avg} is defined as the average thickness of all major ice features (level ice, ice ridges, openings) over the whole leg. H_{eq_max} , in turn, is defined as the average thickness of the same ice features over the part of the leg with the most difficult ice conditions (e.g. an area with severe ice ridging). The application of the concept of equivalent ice thickness rests on the assumption that an ice cover of a specific equivalent ice thickness results in the same level of hull resistance as continuous level ice of the same thickness (Riska, 2010).

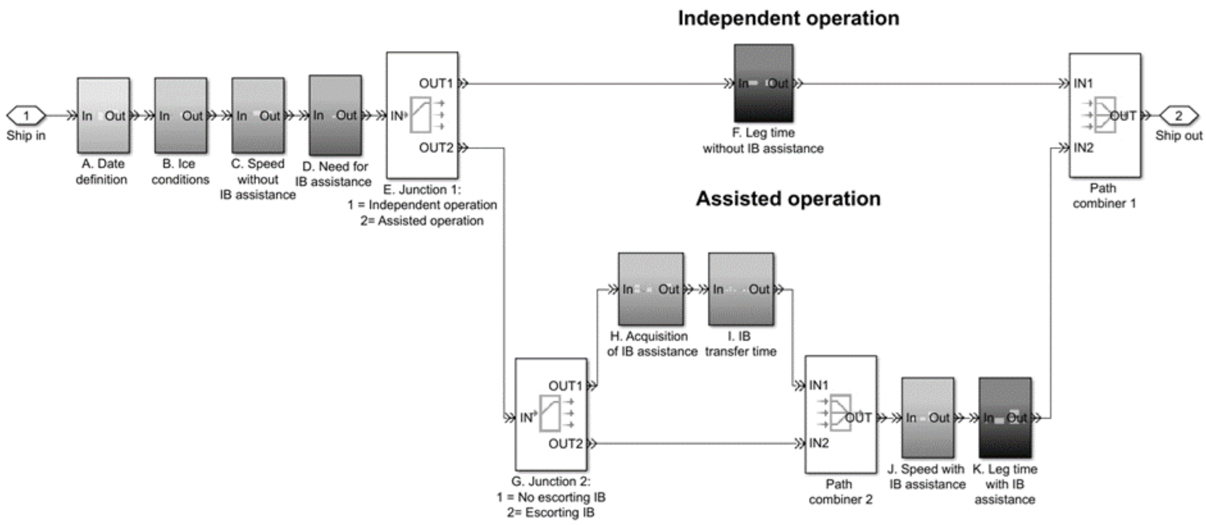

Figure 4: Leg model structure

C. **Speed without IB assistance.** The assumed independently achievable speed of a vessel is determined both for H_{eq_avg} and H_{eq_max} based on ship and operation type-specific *hv*-curves determining the speed of the ship as a function of the ice thickness. As per Figure 5, two different types of independent operation are considered:

   a. Independent operation in a brash ice channel (´Channel' as per Figure 5). Here the ship is operating in a pre-existing brash ice channel without IB assistance. Ice resistance is higher than when operating with IB assistance because broken ice is distributed over the channel area. H_{eq} relates to the prevailing thickness of the unbroken ice in the area.

   b. Independent operation in level ice or through a large ice floe (´Level ice' as per Figure 5).

D. **Need for IB assistance.** Whether a ship needs IB assistance (or continued assistance in case the ship is already assisted by an IB) to complete the upcoming leg is determined based on its estimated independently achievable speed in the worst expected ice conditions (H_{eq_max}) along the leg (calculated in block C). If the estimated independently achievable speed of a ship in H_{eq_max} is below a defined threshold (e.g. 1.5 knots), the ship is considered in need of IB assistance. Otherwise, the ship is considered able to continue independently.

E. **Junction 1.** A ship entity's choice of path at Junction 1 depends on whether the ship that it represents is considered in need of IB assistance. If the represented ship can continue independently, the ship entity continues to block F. In this case, if the ship is assisted by an IB, the resource representing the assisting IB is released from the ship entity and becomes available to assist other ships. On the other hand, if the represented ship is considered in need of IB assistance, the ship entity will proceed to block G.

F. **Leg time without IB assistance.** While operating independently, the time a ship needs to complete a leg is calculated based on the leg distance and the ship's independently achievable speed (determined in block C). The ship entity will remain in the block for a period corresponding to the calculated leg time.

G. **Junction 2.** A ship entity's choice of path at junction 2 depends on whether the ship that it represents is assisted by an IB. If the ship is assisted by an IB, the ship entity continues to block J. Otherwise, it continues to block H.

H. **Acquisition of IB assistance**. A ship entity arriving at block H will trigger a call for IB assistance and wait until an IB resource becomes available. The block may contain multiple ship entities waiting for an IB to become available. IB resources are assigned to ship entities on a one-by-one, first-come, first-served, basis. This means that IBs are assumed to assist one ship at a time. Once a ship entity has been assigned an IB it will proceed to block I.

I. **IB transfer time.** Because available IBs are assumed to be anywhere within their operating area, the exact position from which an IB starts to move towards a ship calling for assistance is not known. Therefore, the related 'transfer time' is determined probabilistically based on an assumed time distribution. The ship entity will remain in the block for a time corresponding to the determined transfer time.

J. **Speed with IB assistance.** The speed of a ship assisted by an IB is determined as the lower of the achievable speed of the assisted ship and the achievable speed of the assisting IB. In other words, the speed is either limited by the assisted ship or by the assisting IB. The achievable speed of the assisted ship is determined based on a ship type specific *hv*-curve for ´Assistance at distance', examples of which are presented in Figure 5. The achievable speed of the IB is determined as per the description of element C – 'Speed without IB assistance'.

K. **Leg time with IB assistance.** The leg time for an IB assisted ship is determined based on the leg distance and the speed of the convoy as determined in block J. The ship entity will remain in the block for a time corresponding to the calculated leg time.

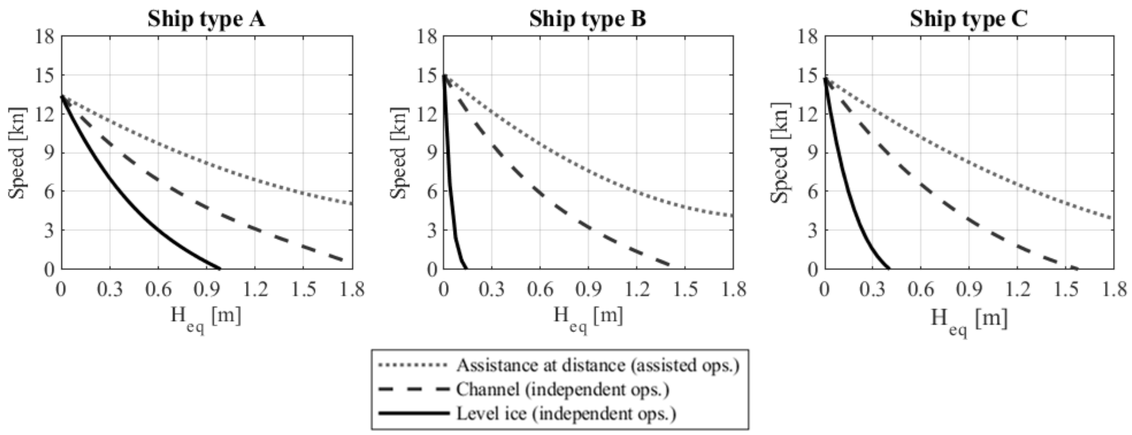

Figure 5: Examples of *hv*-curves for different ship types

As per Figure 3, IBs are assumed to operate within a limited IB operating area. In the simulation, this means that once an IB resource has assisted a ship entity to the border of its operating area, it will leave the ship. If further assistance is needed, a ship entity will request an IB resource from within the IB operating area that it is entering. Thus, in line with the available maritime traffic data, a ship entity might be assisted by several different IB resources on its way towards its destination. In this case, the total waiting time for IB assistance is the accumulated sum of the waiting times related to each instance of IB assistance.

3.3 Generalizations and assumptions

Because of the complexity of the FSWNS, as well as due to various knowledge gaps and technical limitations of the applied simulation technique, the simulation model simplifies and generalises some of the characteristics and mechanisms of the FSWNS including the following:

- Multi-ship convoy operations. In the real world, under certain conditions, convoy operations in which an IB assist multiple ships at a time are used to increase the overall efficiency of the FSWNS. However, in the simulation, the consideration of such multi-ship convoy operations is challenging because it is not clear under what conditions such operations may occur. The ice resistance of a ship being assisted by an IB tends to increase as a function of the distance between the ship and the assisting IB. Therefore, because a significant safety distance is required between ships operating in a convoy, multi-ship convoy operations require a higher ice-going capability from the involved ships (Goerlandt , et al., 2017). As a result, considering the EEDI regulations and other measures lowering the average ice-going capability of ships, convoy operations are expected to remain rare in the future, especially during periods of heavy ice conditions. For this reason, the exclusion of multi-ship convoy operations is not expected to significantly reduce the accuracy of the simulation model when applied to simulate heavy ice condition scenarios.

- IB transit times. Due to limitations set by the applied simulation technique, the exact location from which an available IB starts to move towards a ship in need of IB assistance is not known. Therefore, the duration of the IB transit is determined probabilistically based on statistics. In real life, the master of an IB would try to minimize a ship's waiting time by predicting where assistance will be required next and if possible, start to proceed towards that area in advance. Thus, particularly in periods of relatively low demand for IB assistance, the above-described approach is likely conservative. On the other hand, in periods of high demand for IB assistance, IB waiting times appear to be primarily driven by the availability of IBs, meaning that the relationship between transit times and ships' total IB waiting times is small.

- Criteria for providing of IB assistance. In the simulation, IB assistance is provided if a ship's independently achievable speed falls below a specific limit value (e.g. 1.5 knots) in the worst assumed ice conditions along a leg. In the real world, the criteria for IB assistance likely depends on the operating situation so that the criteria are higher during times of high demand for IB assistance. In addition, the decision on whether IB assistance is to be provided, or requested, is also likely influenced by the individual judgement of the masters of the involved vessels.

- Active measures by the crew. As per the simulation model structure presented in Figure 3, the network of routes along which ships operate throughout a simulation is assumed fixed. This means that active crew measures, such as manoeuvrings to avoid local areas with difficult ice conditions, are not considered. As a result, particularly for sea areas with partially ice-covered waters, the simulation outcome can be assumed conservative.

4 Validation

4.1 Approach

Validation of the model is carried out based on real-world maritime traffic data obtained through WINMOS II (2017) covering maritime traffic on the Bothnian Bay in the period 15.01-15.02.2010. The accuracy of the model is assessed by comparing simulated and data-based performance indicators, such as the number of port arrivals, the number of instances of IB assistance, and IB waiting times. All considered maritime traffic data is presented in Annex A.

4.2 Simulation input

4.2.1 Maritime traffic

Information on ships entering the Bothnian Bay is specified based on the above-mentioned maritime traffic data, an extract of which is presented in Table 2. The entry time is specified in hours from the start of the simulation at midnight 15.01.2010. As per Figure 6, ships arriving from the south (Kvarken) are assumed to enter the considered area at point A, whereas ships arriving from the northwest (northern Sweden) are assumed to enter at point B. Entered ships visit 1-3 ports before they leave the system. The total duration of each port visit is determined in terms of their port turnaround time (PTT) as specified by the maritime traffic data.

Table 2: Extract of maritime traffic data

Entry time, Point A [hr]	Ship model	Port 1	Port 2	Port 3	PTT 1 [hr]	PTT 2 [hr]	PTT 3 [hr]
76	F	Kokkola			73		
83	G	Raahe	Tornio		64	19	
91	C	Oulu			19		
91	G	Tornio	Kotka		25		
91	G	Kemi			28		
92	G	Kokkola	Kemi		60	53	

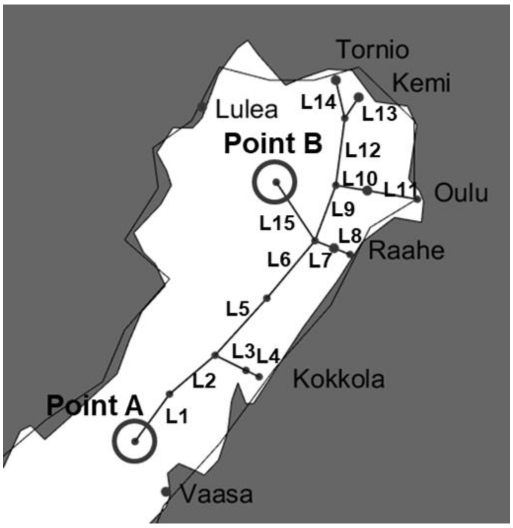

Figure 6: Navigation legs (L) and ports

4.2.2 Ship performance data

The considered maritime traffic data covers ships representing some 16 different types. As per Figure 7, the achievable speed in ice of each ship type is determined in terms of ship type specific *hv*-curves representing three different modes of operation: (a) IB assistance at distance, (b) operation in an ice channel (brash ice), and (c) independent operation in level ice. All *hv*-curves were determined by WINMOS II (2017) based on ice resistance formulas and design particulars of the actual ships.

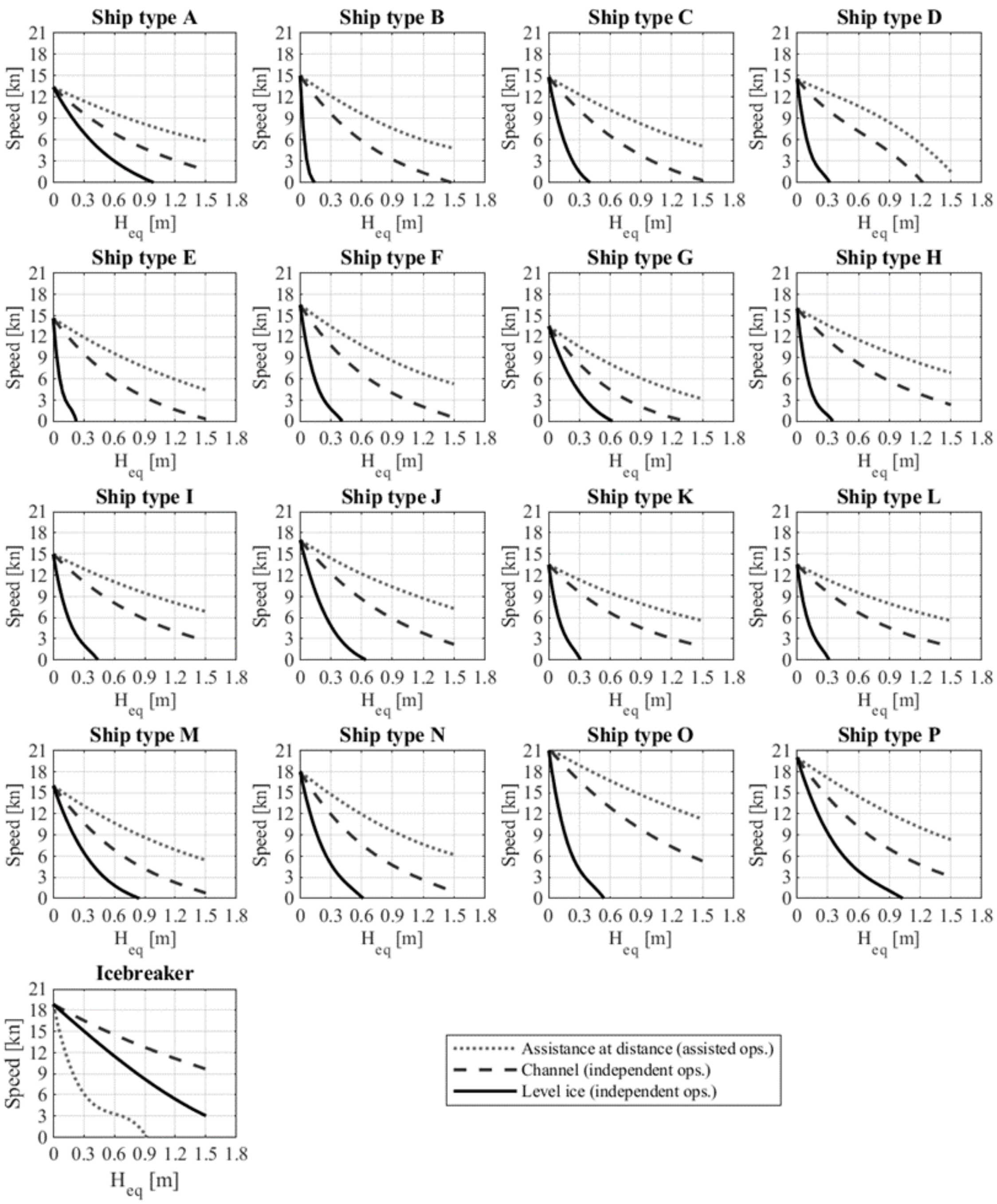

Figure 7: Ship type-specific *hv*-curves for three different operation modes: (a) IB assistance at distance, (b) operation in an ice channel (brash ice), and (c) independent operation in level ice.

4.2.3 Ice conditions

Date and navigation leg specific ice conditions are determined based on ice charts provided by SMHI (2018), an example of which is presented in Figure 8. The ice conditions occurring along a leg on a specific date are determined in terms of the average ice conditions H_{eq_avg} and the most difficult ice conditions H_{eq_max}.

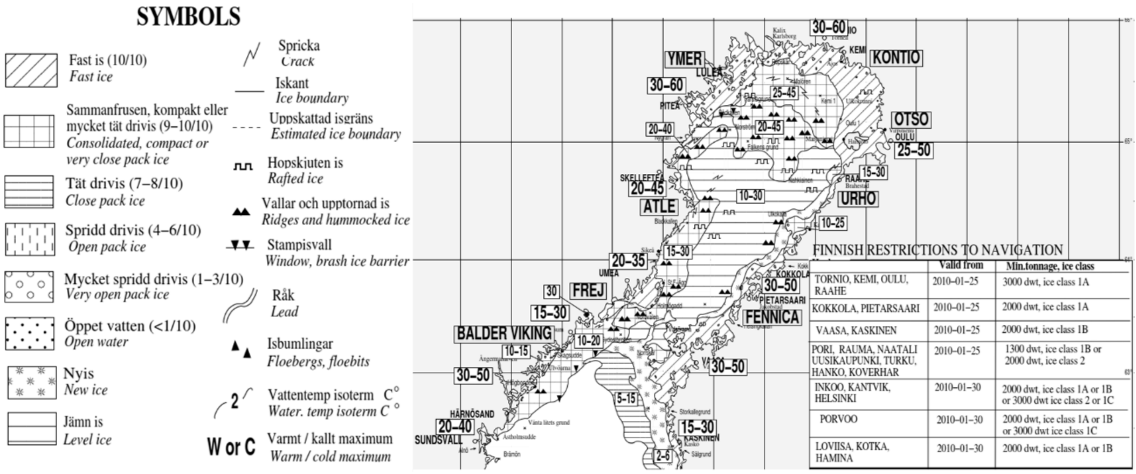

Figure 8: Example ice chart from 05.02.2010 based on SMHI (2018).

The average ice conditions along a leg H_{eq_avg} is determined as per Eq. 2.

$$H_{eq\_avg} = \frac{H_{min}+H_{max}}{2} * \frac{C_{min}+C_{max}}{2} + H_{ridging\_avg}, \qquad (2)$$

, where H_{min} represents the minimum ice thickness, H_{max} represents the maximum ice thickness, C_{min} represents the minimum ice concentration, C_{max} represents the maximum ice concentration, and $H_{ridging\_avg}$ is an assumed 6 cm increase in equivalent ice thickness caused by ridges (where ice ridging occurs). The assumed value of $H_{ridging\_avg}$ is based on Kankaanpää (1997), according to whom ice ridges in the Bothnian Bay increase the level ice thickness by 6-14 cm equivalent ice thickness.

The most difficult ice conditions occurring along a leg H_{eq_max} is determined as per Eq. 3.

$$H_{eq\_max} = H_{max} * C_{max} + H_{ridging\_max}, \qquad (3)$$

, where H_{max} represents the maximum ice thickness, C_{max} represents the maximum ice concentration, and $H_{ridging\_max}$ is an assumed 14 cm increase in level ice thickness caused by ridges (where ice ridging occurs) (Kankaanpää, 1997).

Extracts of calculated and applied H_{eq_avg} and H_{eq_max} values are presented in Table 3 and Table 4. The complete ice data is found in Annex B.

Table 3: Extract of H_{eq_avg} [cm] values

Date	L 1	L 2	L 3	L 4	L 5	L 6	L 7	L 8	L 9	L 10	L 11	L 12	L 13	L 14	L 15
2.2.2010	4	5	5	33	5	5	5	38	21	32	38	21	38	38	43
3.2.2010	4	5	5	33	5	5	5	38	21	32	38	21	38	38	43
4.2.2010	4	5	5	33	5	5	5	38	21	32	38	21	38	38	43
5.2.2010	23	23	23	40	23	23	23	38	23	38	38	39	45	45	45
6.2.2010	23	23	23	40	23	23	23	38	23	38	38	39	45	45	45
7.2.2010	23	23	23	40	23	23	23	38	23	38	38	39	45	45	45

A ship operating in ice may, in addition to natural ice features, encounter ice channels created and maintained by IBs and other ships. The duration for which an ice channel remains open and navigable depends on multiple factors including the amount of maritime traffic, the local geography, as well as the prevailing wind and currents (USCG, 1946). Also, strong winds in combination with a physical boundary might result in compressive ice, which may significantly increase a ship's ice resistance. Anyhow, due to a lack of related data and engineering models, such factors are not systematically considered in this study. Instead, it is assumed that along fairways with significant traffic (L 1, 2, 3, 5, 6, 9, 10, 12, 13, and 14), an open ice channel (brash ice) is available with a 50 % probability. On the open sea, where the traffic is limited (L 15), ice channels are assumed not to be present. In protected waters with fast ice (L 4, 8, and 11), ice channels are assumed to be present throughout the simulation.

Table 4: Extract of H_{eq_max} values [cm]

Date	L 1	L 2	L 3	L 4	L 5	L 6	L 7	L 8	L 9	L 10	L 11	L 12	L 13	L 14	L 15
2.2.2010	5	5	5	40	5	5	5	50	30	30	50	30	50	50	54
3.2.2010	5	5	5	40	5	5	5	50	30	30	50	30	50	50	54
4.2.2010	5	5	5	40	5	5	5	50	30	30	50	30	50	50	54
5.2.2010	36	36	36	50	36	36	36	50	36	50	50	50	60	60	59
6.2.2010	36	36	36	50	36	36	36	50	36	50	50	50	60	60	59
7.2.2010	36	36	36	50	36	36	36	50	36	50	50	50	60	60	59

4.2.4 IB transfer times

Due to a lack of available real-world data, the time it takes for an available IB to reach a ship in need of assistance, in the following referred to as IB transfer time, is determined based on statistics of simulated transfer times obtained from WINMOS II (2017). In accordance with the obtained data, IB transfer times are assumed to be exponentially distributed as per the probability density function (PDF) in Figure 9. Accordingly, the time it takes for an available IB to reach a ship in need of assistance is assumed to be in the range of 0 - 8 hours. The maximum transfer time may correspond to a situation where an IB must cover some 80 NM at an average speed of 10 knots to reach a ship in need of assistance. This distance is roughly equivalent to, for instance, the distance L 1 – L 4 (see Figure 6).

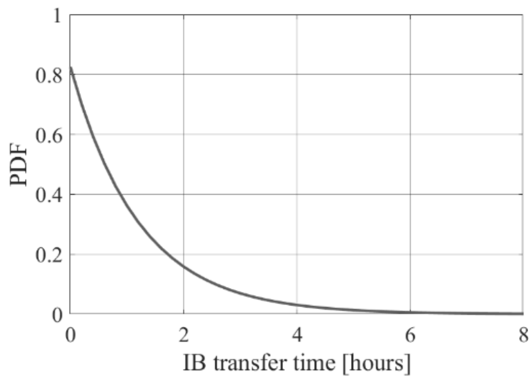

Figure 9: Probability density function (PDF) of IB transfer times determined based on simulated data obtained from WINMOS II (2017).

4.2.5 IB assistance parameters

As per ice charts provided by SMHI (2018), during the considered period, IB assistance is provided in the Bothnian Bay by four IBs: Fennica, Urho, Otso, and Kontio. However, as a simplification, in the simulation all icebreakers are assumed to have an ice-going capability corresponding to that of Otso. The IBs are assumed to operate within their operating area as defined by Figure 3. IB assistance is provided to those ships whose independently achievable speed would fall below 1.5 knots in the worst ice conditions (H_{eq_max}) along a leg.

4.3 Validation results

4.3.1 Real-life vs. simulated number of port visits

A comparison between simulated and real-life ship arrivals per destination port is presented in Figure 10a. As per the figure, the simulated values agree well with the data. This indicates that the simulation model correctly directs the traffic flows within the model and that the simulated ship transit times are similar to or lower than the real-life transit times.

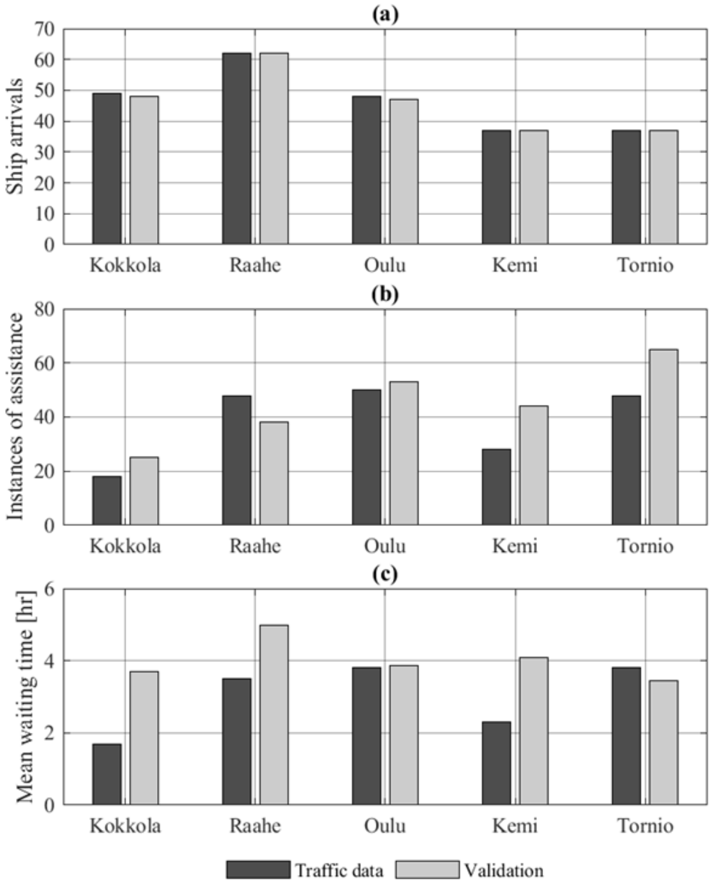

Figure 10: Real-life vs. simulated number of arrived ships per port.

4.3.2 Real-life vs. simulated number of assisted voyages

A comparison between the real-life and the simulated number of instances of IB assistance per destination port is presented in Figure 10b. The presented numbers include all instances of IB assistance received by ships on their way to or from the various ports. Because ships are often assisted at multiple times during a single voyage, the number of instances of assistance is higher than the number of ships that received assistance. As shown by the figure, for some ports (e.g. ports of Kokkola and Oulu) the simulated values agree quite well with the data, whereas for other ports (e.g. ports of Kemi and Tornio), the deviation is larger. The overall standard deviation between the simulation and the data is 11 %.

4.3.3 Real-life vs. simulated IB waiting times

A comparison between the actual and simulated mean IB waiting times is presented in Figure 10c. The presented values correspond to the mean waiting time for all instances of IB assistance related to a ship heading to or leaving from a given port. As shown by the figure, for some ports (e.g. the ports of Oulu and Tornio) the simulated values agree well with the maritime traffic data, whereas for other ports (e.g. port of Kokkola), the deviation is larger. The overall standard deviation between the simulation and the data is 22 %.

In the case of the port of Kokkola, the simulated mean waiting time is significantly larger than the corresponding real-life value. In the simulation, many ships need to pass through leg 1, 2, 3, and 6 (see Figure 6), resulting in extended IB waiting times. In the real-life, this is perhaps avoided due to the presence of open ice channels reducing the need for IB assistance, or by skilful navigation decisions minimizing the exposure to areas with difficult ice conditions, something not considered in the simulation.

4.3.4 Validation summary

The above validation indicates that the proposed approach works in principle. Regarding the number of ship arrivals per port, the simulation agrees well with the data. Regarding the number of instances of IB assistance and IB waiting times, the overall standard deviation between the simulation and the data is 11 % and 22 %, respectively.

Naturally, some of the deviations might relate to factors not considered in the simulation, such as compressive ice conditions and consolidated ice channels that may increase the demand for IB assistance. For instance, the maritime data indicates that tug-barge combinations operating between Raahe and Luleå have received IB assistance in ice conditions in which they in the simulation were able to operate independently. It should also be noted that the available maritime data, or the interpretation thereof, may include some errors. For instance, occasionally it is reported that a ship has received multiple instances of IB assistance during its inward voyage, but none during its outward voyage even thou both voyages would have occurred in similar ice conditions. Also, occasionally it appears like the data, instead of including all instances of IB assistance received by a ship on its way to or from a port, only includes the last or the first instance of IB assistance before port arrival or after departure. Further studies are needed to identify and address such possible inconsistencies.

5 Case study: Analysis of the effect of the EEDI on the performance of the FSWNS

A case study is carried out to demonstrate how the proposed approach can be applied to assess the influence of the EEDI on the performance of the FSWNS.

As the EEDI is enforced on new ships only, the existing fleet of ships will only gradually be replaced by EEDI compliant ships. The case study is carried out for a scenario where about one third (33 %) of arriving ships, randomly selected, are replaced by new EEDI compliant ships. It is further assumed that the achievable speed in ice of new EEDI compliant ships is dependent on their size in DWT as per Figure 11. Accordingly, it is assumed that EEDI compliant ships are not able to operate independently in unbroken level ice. Also, as per the example presented in Figure 12, it is assumed that the speed of an EEDI compliant ship, when operating in an ice channel or with IB assistance, might be significantly lower than that of a corresponding non-EEDI ship. During the simulation, 29 % of the replaced vessels were in the category DWT < 5,100, 61 % were in the category DWT 5,100 – 15,000, and 10 % were in the category DWT 15,000-22,000.

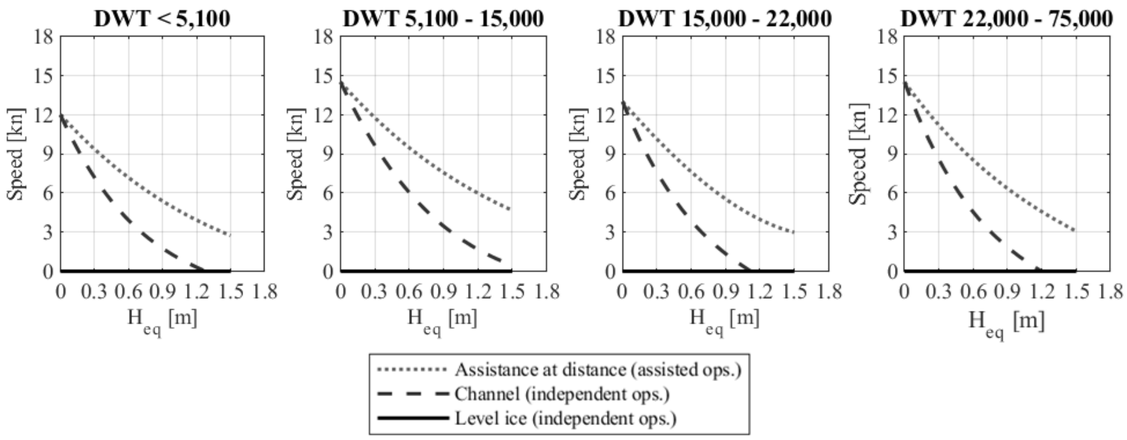

Figure 11: Assumed speed in ice of EEDI compliant ships.

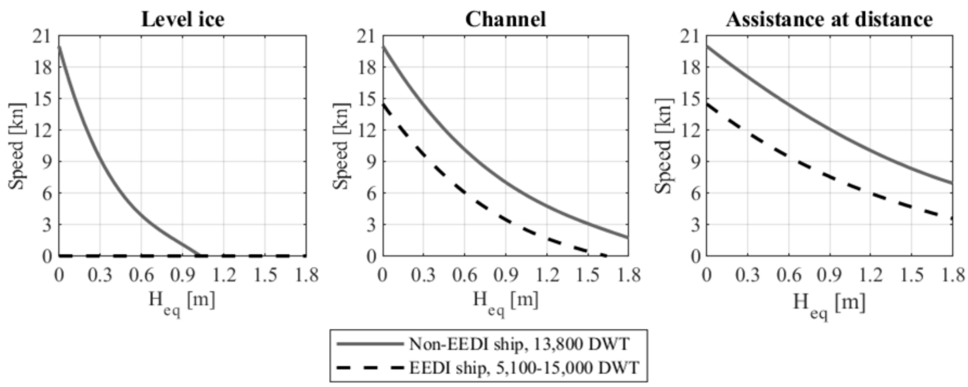

Figure 12: Example comparison of the assumed speed in ice of a non-EEDI ship and an EEDI compliant ship.

The outcome of the simulated EEDI scenario is presented in Figure 13. In comparison with the non-EEDI scenario, as per the simulation in the EEDI scenario the total number of cases of IB assistance increases from 225 to 328 (+ 46 %) and the average waiting times for IB assistance increases from 4.0 hours to 6.9 hours (+ 73 %). The number of ship arrivals per port remained unchanged.

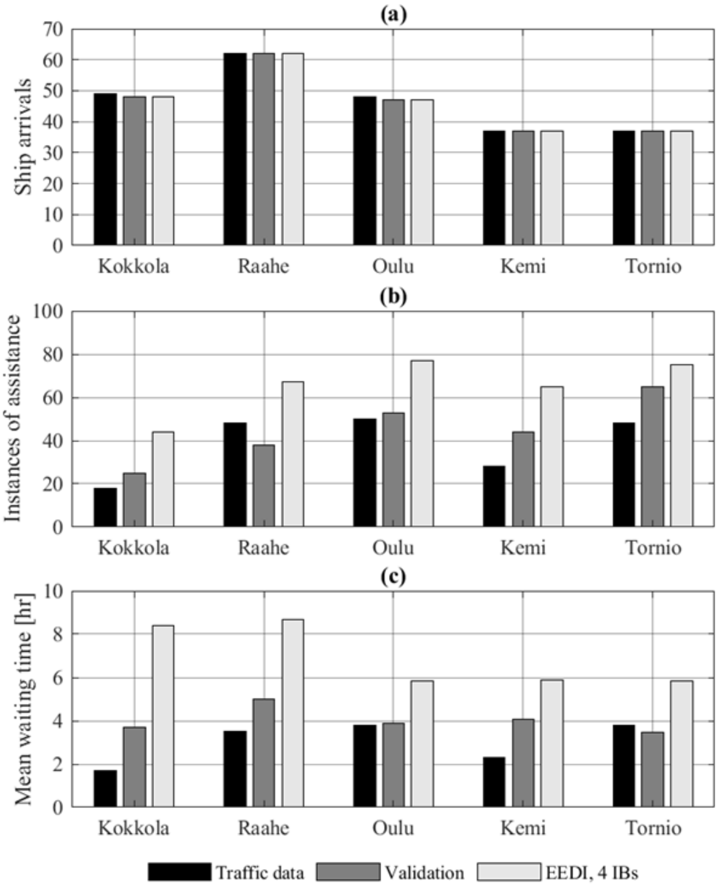

Figure 13: Effect of the EEDI scenario on the number of arrived shiploads

A simulation was carried out to assess whether the increase in IB waiting time from the assumed EEDI scenario could be mitigated by increasing the number of IBs. The outcome from the simulation, presented in Figure 14, indicates that, for the assumed EEDI scenario, an extended IB waiting time could be mitigated by increasing the number of IBs from 4 to 5. Notwithstanding, due to a lack of relevant data, this assessment is based on generalizing and conservative assumptions concerning the effect of the EEDI on the ice going capability of individual ships. Thus, this case study serves mainly as an example of how the presented approach can be applied to assess the performance of the FSWNS under various operating scenarios.

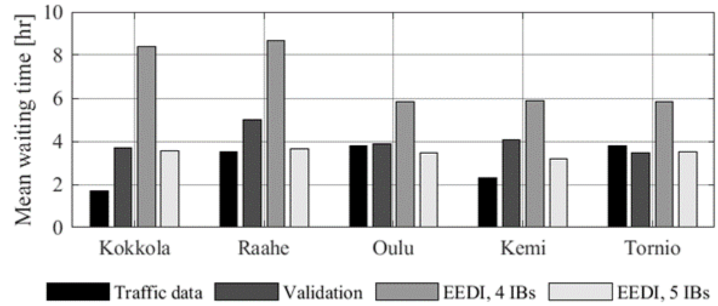

Figure 14: Simulated effect of the EEDI on the transport capacity of the FSWNS.

6 Conclusions

This report presents a simulation-based approach to predict the operating performance of the FSWNS under different operating scenarios. The approach is validated against real-life data on maritime traffic in the Bothnian Bay in the period 15.01-15.02.2010. In terms of the number of ship arrivals per port, representing the transport capacity of the FSWNS, the simulation agrees well with the data. However, in terms of the number of instances of IB assistance and IB waiting times, the deviation between the simulation and the data is significant with standard deviations of 11 % and 22 %, respectively.

Due to various knowledge gaps as well as due to technical limitations of the applied simulation approach, the simulation model is based on generalized assumptions about convoy operations (convoys not considered), IB transfer times (probabilistically determined), criteria for providing IB assistance (generalized criteria), and assumptions concerning the presence of pre-existing ice channels (generalized assumptions). Future research is needed to address these limitations.

Considering its present limitations, the proposed approach appears best suited for scenario-based assessments in which the performance of the transport system is assessed for a limited period (e.g. one month) with heavy ice conditions during which the main shipping routes can be assumed fixed. The outcome of such a scenario-based assessment may indicate whether the capacity of the FSWNS under the simulated conditions is sufficient to keep the system in 'balance'.

A case study was carried out in which the presented approach was applied to assess the effect of a potential future scenario in which around one third (33 %) of the present fleet of merchant ships entering the Bay of Bothnia is replaced by EEDI compliant ships. The case study indicates that the considered EEDI scenario would, in comparison with the default scenario, increase the total number of cases of IB assistance from 225 to 328 (+ 46 %) as well as increase the average waiting times for IB assistance from 4.0 hours to 6.9 hours (+ 73 %). The case study also indicates that the predicted increase in IB waiting times can be mitigated if the number of IBs operating in the area is increased from 4 to 5. However, due to a lack of detailed data on how the EEDI will affect the ice-going capability of ships, the outcome of the analysis is not conclusive.

In summary, the presented approach may provide new insights into the behaviour and performance of the FSWNS under different operating scenarios. A strength of the approach is that it in principle allows quick analysis of multiple different operating scenarios, e.g. with regards to ice conditions, traffic volumes, IB availability, and regulations such as the EEDI. Notwithstanding, for improved accuracy and reliability of the approach, additional research and development are needed.

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Annex A: Maritime traffic data

Table 5: List of ships arriving from Kvarken (Point A as per Figure 6)

Entry time, point B [hr]	Ship model	Port 1	Port 2	Port 3	PTT 1 [hr]	PTT 2 [hr]	PTT 3 [hr]
1	I	Raahe			43		
1	A	Raahe			51		
1	P	Oulu	Kemi		5	4	
1	K	Kokkola			14		
5	N	Kokkola			48		
10	K	Kemi			100		
24	N	Tornio			46		
27	C	Oulu			14		
29	K	Kemi			60		
40	K	Raahe			61		
40	P	Kemi	Oulu		7	7	
48	C	Kemi	Kotka		21		
53	K	Tornio			77		
57	G	Kokkola	Raahe		26	61	
59	I	Kokkola			12		
63	K	Kokkola			31		
65	G	Raahe			89		
66	G	Kokkola			86		
69	M	Kokkola			20		
72	N	Kokkola			48		
74	K	Tornio			21		
76	F	Kokkola			73		
83	G	Raahe	Tornio		64	19	
91	C	Oulu			19		
91	G	Tornio	Kotka		25		
91	G	Kemi			28		
92	G	Kokkola	Kemi		60	53	
93	G	Kokkola			31		
95	O	Kemi	Oulu		4	12	
97	K	Tornio	Kemi		22	36	
99	K	Tornio			22		
101	C	Kokkola			50		
108	K	Raahe			69		
111	G	Raahe			51		
113	K	Kokkola			43		
119	K	Oulu			35		
122	K	Oulu			108		
125	G	Kokkola	Kemi	Oulu	35	73	65
126	K	Tornio			19		

133	G	Tornio			65		
134	A	Raahe			162		
135	K	Tornio	Raahe		22	30	
139	L	Kemi			51		
140	C	Oulu			19		
144	N	Oulu			34		
152	L	Oulu			17		
156	P	Oulu	Kemi		6	8	
157	G	Kemi			122		
157	G	Raahe			68		
158	K	Kokkola			27		
160	C	Kemi			30		
165	G	Raahe	Oulu		51	41	
167	N	Oulu			23		
172	K	Tornio			41		
178	K	Oulu			17		
182	F	Kokkola			32		
192	N	Raahe			52		
200	K	Kokkola			81		
200	K	Kokkola			76		
206	P	Oulu	Kemi		8	7	
207	J	Kokkola			64		
207	A	Raahe			57		
214	K	Kokkola	Raahe		15	48	
220	G	Tornio	Kokkola		50	55	
224	M	Raahe			34		
228	F	Kokkola			18		
228	K	Kokkola			97		
228	C	Oulu			-3		
228	C	Raahe	Pori		43		
230	G	Tornio			66		
235	C	Oulu			6		
235	C	Kokkola			7		
242	N	Oulu	Tornio		78	21	
243	I	Raahe			27		
244	G	Tornio	Raahe		20	49	
249	K	Tornio	Kemi		28	40	
250	K	Oulu			73		
260	B	Kokkola			54		
261	L	Kokkola			18		
262	O	Kemi	Oulu		7	7	
263	K	Tornio	Kotka		45		
266	P	Kemi			116		
268	M	Raahe			69		

275	G	Kokkola			64		
278	K	Tornio	Raahe		44	88	
293	G	Tornio			65		
298	C	Kokkola			24		
310	L	Oulu			18		
311	K	Oulu	Kemi		31	68	
319	K	Raahe			54		
321	K	Oulu	Pori		70		
323	P	Oulu	Kemi		10	11	
332	K	Kokkola			71		
336	A	Raahe			47		
337	B	Kokkola			24		
339	I	Kemi			17		
352	G	Kokkola			111		
360	N	Oulu			34		
364	K	Kokkola			21		
370	P	Kemi	Oulu		7	8	
374	M	Kokkola			22		
383	C	Kokkola			7		
384	N	Tornio			46		
393	N	Oulu	Tornio		104	23	
394	F	Raahe	Kokkola		41	65	
401	K	Tornio					
407	G	Kemi	Raahe		32	4	
419	E	Oulu			14		
419	A	Raahe			40		
424	G	Kokkola			94		
425	G	Tornio	Raahe		32	47	
426	P	Oulu			6		
434	B	Tornio	Raahe	Pori	147	29	
448	G	Tornio			79		
455	K	Kokkola			29		
457	A	Raahe			37		
470	J	Kokkola			64		
473	K	Kemi	Oulu		82	50	
474	K	Raahe			64		
481	K	Raahe			73		
486	B	Kokkola			17		
486	K	Tornio			29		
490	G	Kemi			39		
493	G	Oulu			84		
496	K	Oulu			15		
496	G	Tornio			77		
504	N	Raahe			52		

514	B	Kokkola			239		
514	P	Oulu	Kemi		9	7	
519	H	Kemi			145		
531	K	Raahe	Tornio		18	79	
536	P	Kemi	Oulu		8	10	
542	C	Oulu			22		
543	K	Raahe	Tornio		45	23	
554	G	Raahe	Oulu		25	58	
562	K	Raahe	Kokkola				
563	K	Tornio			47		
563	K	Raahe			8		
567	N	Oulu	Tornio		101	45	
574	K	Raahe			68		
576	G	Oulu			74		
576	N	Oulu			34		
577	G	Kemi	Tornio		44	23	
584	G	Tornio			67		
588	K	Kokkola			19		
593	L	Oulu			21		
593	K	Kemi	Oulu		52	45	
595	O	Kemi	Oulu		9	7	
596	H	Oulu					
610	I	Raahe			14		
621	A	Raahe			15		
626	C	Kokkola			49		
629	L	Kemi			17		
630	G	Tornio			65		
636	K	Tornio	Raahe		30	77	
648	N	Tornio			46		
659	G	Raahe			17		
660	M	Kokkola			28		
670	K	Tornio	Kokkola				
679	G	Kemi			51		
681	K	Kemi	Kokkola				
682	P	Oulu	Kemi		8	6	
683	L	Kokkola			15		
701	C	Kemi			15		
708	P	Kemi	Oulu		8	8	
710	F	Kokkola			64		
718	D	Raahe			92		
725	K	Raahe			7		
736	L	Oulu			29		
744	N	Oulu			34		
753	N	Oulu	Tornio				

754	K	Tornio			39		
755	F	Raahe	Kokkola		14	45	
764	G	Kokkola			32		
765	O	Kemi	Oulu				

Table 6: List of ships arriving from northern Sweden (Point B as per Figure 6)

Enry time, point B [hr]	Ship model	Port 1	Port 2	Port 3	PTT 1 [hr]	PTT 2 [hr]	PTT 3 [hr]
31	A	Raahe			39		
67	A	Raahe			15		
110	A	Raahe			29		
137	A	Raahe			33		
155	M	Raahe			18		
164	A	Raahe			49		
249	A	Raahe			21		
371	A	Raahe			48		
388	M	Raahe			12		
455	A	Raahe			49		
455	M	Raahe			11		
541	A	Raahe			18		
593	A	Raahe			18		
608	A	Raahe			40		
645	A	Raahe			43		
686	A	Raahe			74		
737	M	Raahe			40		
758	A	Raahe			52		

Annex B: Ice data

Table 7: H_{eq_avg} [cm] determined by date and leg (L)

Date	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11	L12	L13	L14	L15
15.1.2010	6	14	32	13	29	24	32	30	23	32	30	20	33	33	25
16.1.2010	6	14	32	13	29	24	32	30	23	32	30	20	33	33	25
17.1.2010	6	14	32	13	29	24	32	30	23	32	30	20	33	33	25
18.1.2010	6	14	32	13	29	24	32	30	23	32	30	20	33	33	25
19.1.2010	6	14	32	13	29	24	32	30	23	32	30	20	33	33	25
20.1.2010	6	14	32	13	29	24	32	30	23	32	30	20	33	33	25
21.1.2010	6	14	32	13	29	24	32	30	23	32	30	20	33	33	25
22.1.2010	8	9	10	33	9	9	10	30	23	32	30	20	33	33	32
23.1.2010	8	9	10	33	9	9	10	30	23	32	30	20	33	33	32
24.1.2010	8	9	10	33	9	9	10	30	23	32	30	20	33	33	32
25.1.2010	8	9	10	33	9	9	10	30	23	32	30	20	33	33	32
26.1.2010	8	9	10	33	9	9	10	30	23	32	30	20	33	33	32
27.1.2010	8	9	10	33	9	9	10	30	23	32	30	20	33	33	32
28.1.2010	8	9	10	33	9	9	10	30	23	32	30	20	33	33	32
29.1.2010	4	5	5	33	5	5	5	38	21	32	38	21	38	38	43
30.1.2010	4	5	5	33	5	5	5	38	21	32	38	21	38	38	43
31.1.2010	4	5	5	33	5	5	5	38	21	32	38	21	38	38	43
1.2.2010	4	5	5	33	5	5	5	38	21	32	38	21	38	38	43
2.2.2010	4	5	5	33	5	5	5	38	21	32	38	21	38	38	43
3.2.2010	4	5	5	33	5	5	5	38	21	32	38	21	38	38	43
4.2.2010	4	5	5	33	5	5	5	38	21	32	38	21	38	38	43
5.2.2010	23	23	23	40	23	23	23	38	23	38	38	39	45	45	45
6.2.2010	23	23	23	40	23	23	23	38	23	38	38	39	45	45	45
7.2.2010	23	23	23	40	23	23	23	38	23	38	38	39	45	45	45
8.2.2010	23	23	23	40	23	23	23	38	23	38	38	39	45	45	45
9.2.2010	23	23	23	40	23	23	23	38	23	38	38	39	45	45	45
10.2.2010	23	23	23	40	23	23	23	38	23	38	38	39	45	45	45
11.2.2010	23	23	23	40	23	23	23	38	23	38	38	39	45	45	45
12.2.2010	41	33	33	40	33	33	33	45	33	45	45	39	55	55	52
13.2.2010	41	33	33	40	33	33	33	45	33	45	45	39	55	55	52
14.2.2010	41	33	33	40	33	33	33	45	33	45	45	39	55	55	52
15.2.2010	41	33	33	40	33	33	33	45	33	45	45	39	55	55	52

Table 8: H_{eq_max} [cm] determined by date and leg (L)

Date	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11	L12	L13	L14	L15
15.1.2010	20	20	45	20	30	36	36	40	30	30	40	30	40	40	39
16.1.2010	20	20	45	20	30	36	36	40	30	30	40	30	40	40	39
17.1.2010	20	20	45	20	30	36	36	40	30	30	40	30	40	40	39
18.1.2010	20	20	45	20	30	36	36	40	30	30	40	30	40	40	39

19.1.2010	20	20	45	20	30	36	36	40	30	30	40	30	40	40	39
20.1.2010	20	20	45	20	30	36	36	40	30	30	40	30	40	40	39
21.1.2010	20	20	45	20	30	36	36	40	30	30	40	30	40	40	39
22.1.2010	15	15	15	40	15	15	15	40	44	32	40	44	40	40	44
23.1.2010	15	15	15	40	15	15	15	40	44	32	40	44	40	40	44
24.1.2010	15	15	15	40	15	15	15	40	44	32	40	44	40	40	44
25.1.2010	15	15	15	40	15	15	15	40	44	32	40	44	40	40	44
26.1.2010	15	15	15	40	15	15	15	40	44	32	40	44	40	40	44
27.1.2010	15	15	15	40	15	15	15	40	44	32	40	44	40	40	44
28.1.2010	15	15	15	40	15	15	15	40	44	32	40	44	40	40	44
29.1.2010	5	5	5	40	5	5	5	50	30	30	50	30	50	50	54
30.1.2010	5	5	5	40	5	5	5	50	30	30	50	30	50	50	54
31.1.2010	5	5	5	40	5	5	5	50	30	30	50	30	50	50	54
1.2.2010	5	5	5	40	5	5	5	50	30	30	50	30	50	50	54
2.2.2010	5	5	5	40	5	5	5	50	30	30	50	30	50	50	54
3.2.2010	5	5	5	40	5	5	5	50	30	30	50	30	50	50	54
4.2.2010	5	5	5	40	5	5	5	50	30	30	50	30	50	50	54
5.2.2010	36	36	36	50	36	36	36	50	36	50	50	50	60	60	59
6.2.2010	36	36	36	50	36	36	36	50	36	50	50	50	60	60	59
7.2.2010	36	36	36	50	36	36	36	50	36	50	50	50	60	60	59
8.2.2010	36	36	36	50	36	36	36	50	36	50	50	50	60	60	59
9.2.2010	36	36	36	50	36	36	36	50	36	50	50	50	60	60	59
10.2.2010	36	36	36	50	36	36	36	50	36	50	50	50	60	60	59
11.2.2010	36	36	36	50	36	36	36	50	36	50	50	50	60	60	59
12.2.2010	54	46	46	50	46	46	46	60	46	59	60	59	70	70	64
13.2.2010	54	46	46	50	46	46	46	60	46	59	60	59	70	70	64
14.2.2010	54	46	46	50	46	46	46	60	46	59	60	59	70	70	64
15.2.2010	54	46	46	50	46	46	46	60	46	59	60	59	70	70	64