An approach towards the design of robust arctic maritime transport systems

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ABSTRACT: This paper describes a simulation-based approach towards the design of robust arctic maritime transport systems that are adaptable to uncertain future ice conditions. It makes it possible to simulate the performance of the transport system for various future ice scenarios and to compare various ice mitigation strategies in terms of cost. A case study is carried out to demonstrate how the approach could be applied in practice. The outcome from the case study indicates that the approach can provide valuable insights into the economics of an arctic maritime transport system and that its components can easily be modified or replaced for improved accuracy.

Key words: Arctic ship, arctic maritime transport system, ice class, icebreaker assistance, simulation

1 INTRODUCTION

Shipping in the Arctic is predicted to grow both in volume and diversity over the coming years. This prediction is due to the large oil, gas, and mineral discoveries found in the arctic region, as well as due to the increased interest in the Northern Sea Route.

When designing an arctic maritime transport system, here defined as a system consisting of any number of vessels transporting cargo between two or more ports through partially ice-covered waters, several arctic specific challenges, such as uncertain future ice conditions, need to be considered. To make such a transport system robust, in the sense that it is adaptable to such uncertain future ice conditions, it is necessary to consider a range of various possible future ice conditions along the intended route and to define an ice mitigation strategy that is able to deal with each of those conditions. To this aim, a simulation based approach is developed that can be used to simulate the performance of an arctic maritime transport system for various future ice scenarios and to compare various ice mitigation strategies for those scenarios in terms of cost.

In the current approach, the ice-vessel interaction is limited to the ice resistance, i.e., only the power demand of the vessel is considered. As a simplification, the ice is assumed to be level ice, i.e., possible ridges, ice channels, etc. are not considered. In addition, the ice thickness is assumed to remain constant between consecutive waypoints along the route.

A case study is carried out to demonstrate how the developed approach could be applied in practice. The results of the case study indicate that it can provide valuable insights into the economics of an arctic maritime transport system and that it can be developed further as it´s components can easily be modified or replaced for improved accuracy.

The developed approach can be considered a further development of an approach towards mission-based design of arctic maritime transport systems developed by (Bergström, et.al., 2014), which in turn was partly based on an approach developed by (Erceg, et. al., 2013). Other related work include (Valkonen, et.al., 2013) and (Riska, et.al., 2001).

2 DESCRIPTION OF THE APPROACH

The transport task is defined by the route, the transport demand, and the period of time the transport will be taking place (for instance within the period 2016-2025). The transport route is determined by waypoints (coordinates along the route). Waypoint and date (voyage) specific ice thickness estimates are obtained from ice scenarios determined based on the prevailing ice conditions and various possible future development trends determined by the user.

In case of independent operation in ice, i.e., operation without icebreaker support, the speed of the vessel is calculated using a so-called *h-v* curve described by (Juva, et.al., 2002) that determines the speed of a ship as a function of the ice thickness. The speed of a vessel being escorted by an icebreaker is assumed to correspond to an assumed average speed of the icebreaker. Icebreaker assistance is assumed to be required from the first to the last waypoint along the route where the ice thickness exceeds a specific value determined by the user based on the ice class and the propulsion power of the ship. A flowchart describing the developed approach is presented in Figure 1.

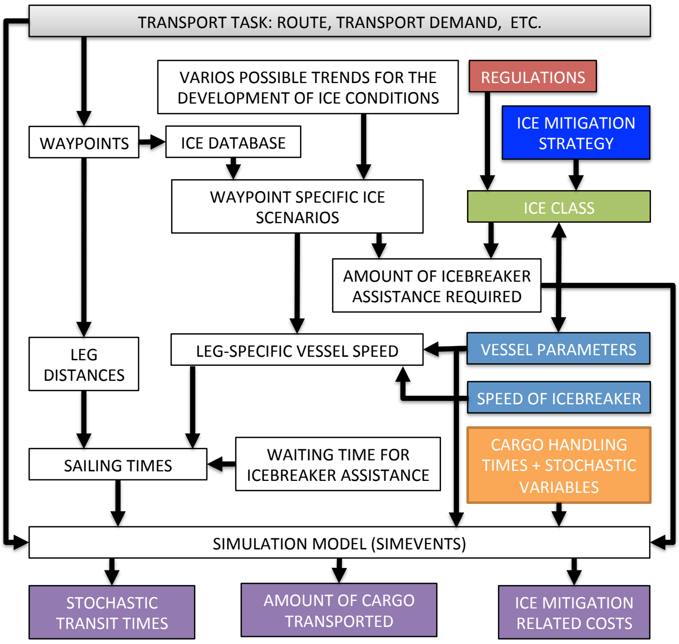

Figure 1. Flow chart describing the developed approach

Possible ice mitigation strategies, i.e., strategies for how to deal with sea ice include for instance the following:

1. Use of ships with a low ice class that are able to operate independently in thin ice only and use of icebreaker assistance when the ice conditions exceeds the class capabilities.
2. Use of ships with a high ice class and propulsion power to reduce/minimize the amount of icebreaker assistance required.
3. Avoidance of difficult ice conditions by limiting the operation to periods with little or no ice.

Costs related to various ice mitigation strategies are calculated based on estimates for the following cost items:

- Daily cost for icebreaker assistance.
- Additional investment and operating cost related to a higher ice class and propulsion power.
- Additional fuel costs due to additional ice resistance.

The total voyage specific sailing times are calculated based on the leg distances and the corresponding leg specific speeds. Calculated sailing times for the time span simulated are then imported into a SimEvents (a discrete event simulation tool developed by MathWorks) simulation model. By using the simulation tool, it is then possible to simulate stochastic transit time including stochastic factors such as time spent waiting for icebreaker assistance, loading and unloading times, variations in the transit time caused by weather etc. Additional parameters can be included as needed.

The simulation model can then be used to simulate how the transit times vary during the time span simulated due to varying ice conditions, to simulate the total accumulated amount of cargo transported from location A to location B, and to simulate the required number of days of icebreaker assistance.

3 CASE STUDY

3.1 *Transport task*

The case study deals with the maritime transport of Liquefied Natural Gas (LNG) from the port of Sabetta (Russia), which is still under construction, to the port of Narvik (Norway), from where the LNG is assumed to be transported onwards. The transport from Sabetta to Narvik is carried out by ice-strengthened LNG carriers, while the onwards transport from Narvik to the large transhipment terminals in central Europe and Asia is carried out by more cost efficient LNG carriers without ice class. The route, which is approximately 1489 NM, is presented in Figure 2.

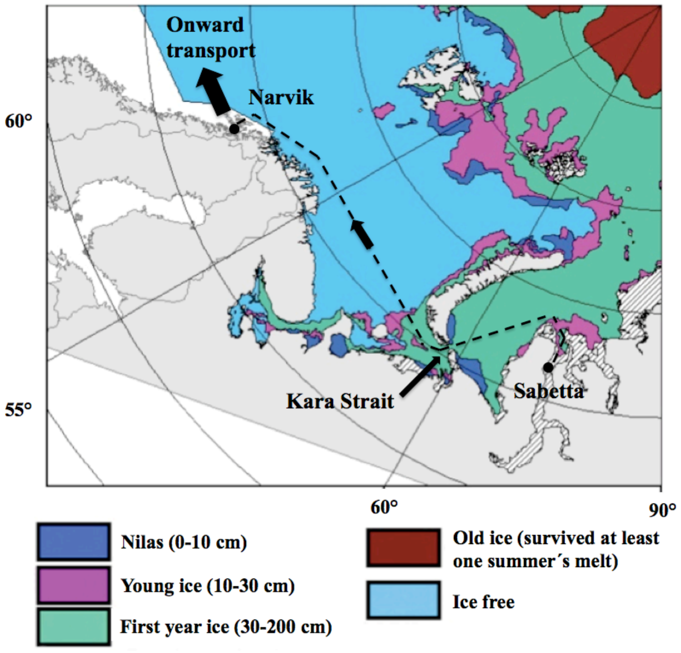

Figure 2. The route of the case study plus ice conditions along the route in mid-march 2014 as determined by (AARI, 2014)

The average LNG production rate in Sabetta is assumed to be 100,000 m3/day (Total S.A., 2014). Thus, to avoid production stops the average transport capacity of the system needs to be at least 100,000 m3/day x 365 days/year = 36,500,000 m3/year. The objective of the case study is therefore to design a transport system with sufficient capacity to avoid production stops resulting in very significant economic losses.

The assumed transport task can be seen as an alternative to the plan to use Arc 7 classified 170,000 m3 LNG carriers to transport the LNG directly from Sabetta to the large transhipment terminals in central Europe and Asia (Renton, M., 2013,). Such heavy ice-strengthened ships are, in open waters, general significantly less cost-effective than lighter non-ice-strengthened ships. Thus, it could be more economical to limit the use of ice-strengthened vessels to the part of the distance where ice strengthening is needed, and carry out the onward transport using normal ships. The planning of the transport system is assumed to be in the conceptual design phase. Operation is assumed to start at January 1 2016 and to continue for at least 10 years. The time span simulated is therefore 01.01.2016 - 31.12.2025.

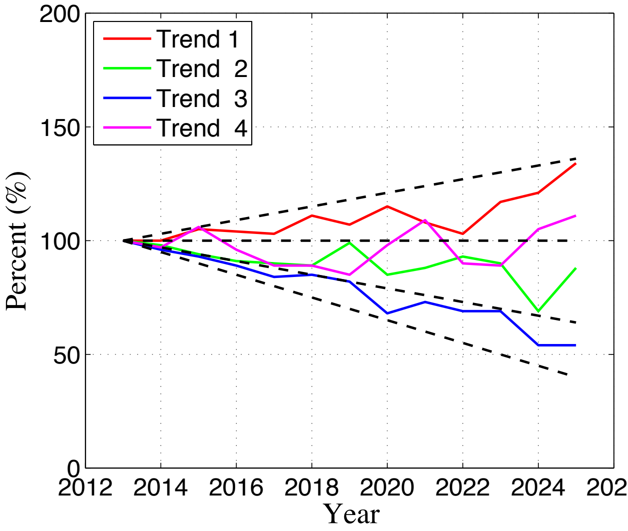

Figure 3. Applied ice thickness development trends

3.2 *Determination of ice scenarios*

The starting point, i.e., the assumed prevailing ice conditions, was determined by modifying ice data obtained from a numerical climate model developed by SINTEF called SINMOD (Slagstad, et.al., 2005) (SINTEF, 2014) to correspond to ice data from satellite imagery from year 2012 and 2013 provided by (AARI, 2014). Based on the assumed prevailing conditions, four possible future ice scenarios were then generated for the time span simulated based on four assumed ice thickness development trends presented in Figure 3. The trends, which include one trend of increasing ice thicknesses, two trends of decreasing ice thicknesses, and one trend of more or less unchanged ice thickness, were determined based on coefficients generated at random between predetermined intervals. Ice scenario specific average ice thicknesses along the distance Kara Strait- Sabetta, where first-year ice occurs, are shown in Figure 4.

3.3 *Ice conditions along the route*

The route goes through the Kara and the Pechora Sea, both of which according to satellite imagery based ice maps provided by (AARI, 2014) are normally covered by first year ice in the winter. An ice map, that was determined based on one of the ice maps from (AARI, 2014) showing the ice conditions along the route in mid-march 2014, is presented in Figure 2.

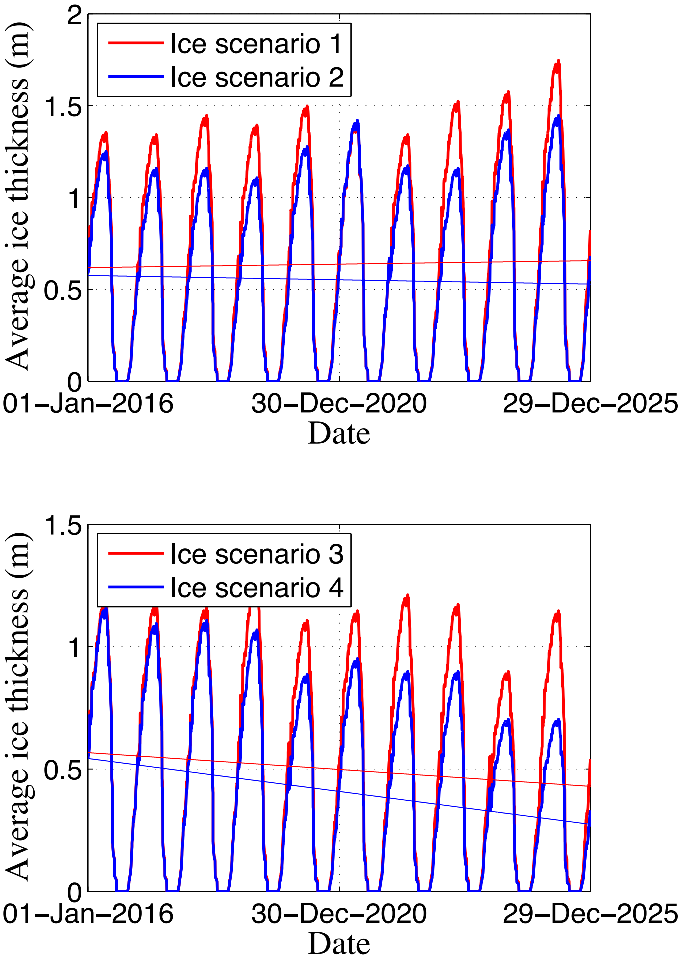

Figure 4. Determined ice scenarios

An example of applied date specific ice forecast for the route is shown in Figure 5, which shows the predicted ice thicknesses along the route for 31.03.2026 in accordance with ice scenario 1. On that date, as shown in Figure 3, the predicted maximum ice thickness along the route is around 2.0 m. This is assumed to be the maximum ice thickness that can occur along the route during the simulated period of time.

The sailing time is determined based on the date of departure, i.e., based on the ice conditions that occur along the route as the ship leaves the harbour. This means that the ice thicknesses estimated for the various legs are assumed to remain constant during a voyage. In addition, the ice thickness is assumed to be homogenous between waypoints, which in the case study are between 7 and 22 nautical miles (nm) apart along the part of the route where ice occur.

3.4 *Ice mitigation strategies considered*

Three different ice mitigation strategies were considered:

1. Use of Polar Class (PC) 7 classed ships that are able to operate independently in up to 0.7 m thick ice. Use of icebreaker assistance when the ice thickness exceeds 0.7 m.
2. Use of PC 5 classed ships that are able to operate independently in up to 1.2 m thick ice. Use of icebreaker assistance when the ice thickness exceeds 1.2 m.
3. Use of PC 4 classed ships that are able to operate independently in up to 1.7 m thick ice. Use of icebreaker assistance when the ice thickness exceeds 1.7 m.

Periods with little or no ice are expected to be very short along the present route. Thus, one of the in section 2 mentioned possible ice mitigation strategies, to avoid difficult ice conditions by limiting the operation to periods with little or no ice, was excluded while it was considered infeasible.

A single icebreaker is assumed to cost USD 50,000 per day. Convoys are not considered, i.e., the icebreaker costs are not divided on multiple ships.

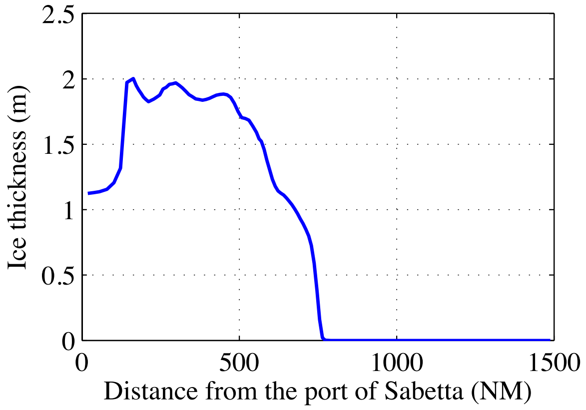

Figure 5. Ice thickness along the route at 31.03.2026 in accordance with ice scenario 1.

3.5 *Estimation of vessel parameters and costs*

The assumed vessel parameters are presented in Table 1. The main dimensions of the vessel were determined based on a LNG carrier of the fleet of Knutsen OAS Shipping (Knutsen OAS Shipping AS, 2014). The initial investment costs were determined assuming that a PC 7 vessel costs 10 % more than a standard vessel without ice class that is assumed to cost USD 220 M. The corresponding additional investment cost for PC 5 and PC 4 vessels are assumed to be 20 % and 30 %, respectively.

The additional operating costs related to PC 5 and PC 4 were determined assuming that the annual operating costs correspond to around 3 % of the initial investment.

The required propulsion power for each ice class were determined so that the ship at 85 % MCR is able to operate with a speed of around 3 kn in the maximum ice thickness for independent operation specified for the ice class in question. The 15 % sea margin can be utilized, for instance, in case the vessel gets stuck in an ice ridge.

Table 1: Assumed ship parameters

Length w.l.	280 m
Breadth	45.8 m
Draft	12 m
Cargo capacity	172,000 m3
Tonnage	110,920 GT
Speed o.w.	19.5 kn
Ice class	PC7/ PC 5/ PC4
Propulsion power at 0.85 % MCR	30,000 kW/ 57,000 kW/ 90,000 kW
Specific fuel consumption (HFO)	180 g/ kWh
Initial investment	USD 242 M/ USD 264 M/ USD 297 M
Annual operating costs related to a higher ice class	USD 0/ USD 3.96 M/ USD 9.9 M

3.6 *Transit times*

Regardless of ice scenario and ice mitigation strategy, the transit times vary significantly between seasons. Simulated transit times for ice scenario 2 and PC 7 vessels are shown as example in Figure 6.

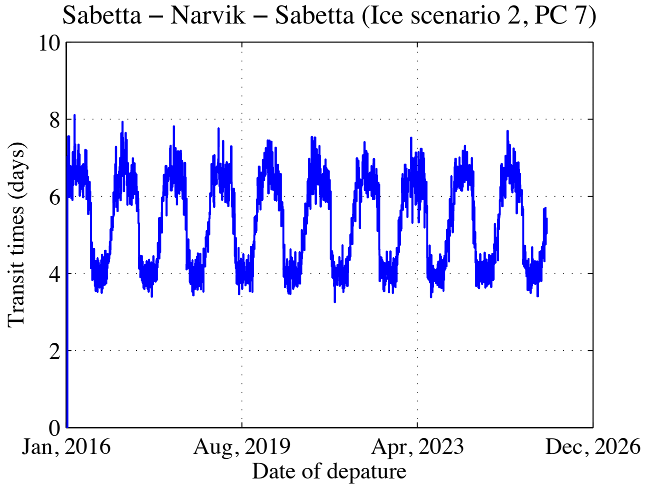

Figure 6. Example of simulated transit times

In this case, the total duration of a return trip varies between 16 days (2 x 8 days) during peak ice conditions and 6.5 days (2 x 3,25 days) during periods with no ice. The average return trip is around 10.2 days (2 x 5.1 days) and the median is around 9.2 days (4.6 x 2 days). Please note that the above-mentioned transit times are examples only. All transit times applied in the simulations are voyage and date specific, i.e., unique.

3.7 *Determination of transport capacity*

The ensure a sufficient transport capacity also in the worst assumed ice conditions, i.e., ice scenario 1, six vessels each with a capacity of 172,000 m3 are, regardless of the polar class of the vessels, needed to meet the transport demand. If the cargo capacity of the vessels is reduced to for instance 165,000 m3, the amount on LNG waiting to be transported from Sabetta will start to increase. This is demonstrated in Figure 7, which in case of ice scenario 1 and use of PC 5 vessels, shows the amount of LNG waiting to be transported from Sabetta for various vessel capacities. As the storage capacity in Sabetta is limited, an increasing amount of LNG waiting for onward transport will eventually enforce a production stoppage. Therefore, assuming the costs related to such a production stoppage are very significant, it was decided that the vessels need to have a capacity of at least 172,000 m3.

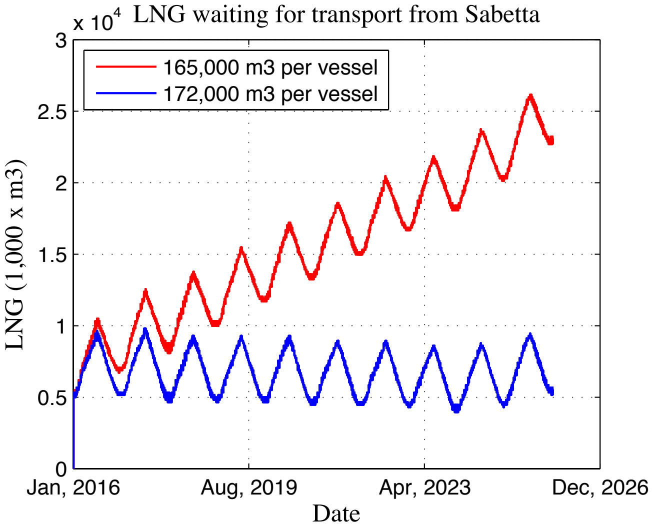

Figure 7. The amount of LNG waiting to be transported from Sabetta for various vessel capacities (Ice scenario 1, PC 5)

The drawback of having a transport capacity that is adjusted to the worst assumed ice conditions is that there inevitable will be some overcapacity in less severe ice scenarios. However, the amount of overcapacity depends on the selected ice mitigation strategy. Thus, the various ice mitigation strategies are in the following investigated to find out which of them is the least sensitive to uncertain future ice scenarios, i.e., which of them represents the most robust solution.

In case of ice scenario 2, in which there is a trend towards decreasing ice thickness, the overcapacity is limited to around 1 % for both PC 5 and PC 7. However, for PC 4, the overcapacity is around 7 %. In case of ice scenario 3, with the least amount of ice, i.e., the overcapacities for PC 7 and PC 5 are around 4 % and 5 % respectively while the overcapacity for PC 4 is up to 13 %. In case of ice scenario 4, in which the ice thickness does neither significantly increase nor decrease, the overcapacity for both PC 7 and PC 5 is around 1 % while the overcapacity for PC 4 is around 5 %. Transport capacity utilization per ship for the various ice scenarios and ice mitigation strategies is presented in Table 2.

Table 2: Capacity utilization per ship for various ice scenarios and ice mitigation strategies

		Capacity utilization per ship	
Ice class	Number of ships	Cubic meters	Percent
Ice scenario 1			
PC 7	6	172000 m3	100%
PC 5	6	172000 m3	100%
PC 4	6	172000 m3	100%
Ice scenario 2			
PC 7	6	170000 m3	99%
PC 5	6	170000 m3	99%
PC 4	6	160000 m3	93%
Ice scenario 3			
PC 7	6	165000 m3	96%
PC 5	6	163000 m3	95%
PC 4	6	150000 m3	87%
Ice scenario 4			
PC 7	6	171000 m3	99%
PC 5	6	171000 m3	99%
PC 4	6	163000 m3	95%

3.8 *Determination of the number of days of icebreaker assistance required*

Icebreaker assistance is assumed to be required when the ice thickness exceeds the maximum ice thickness for independent operation specified for each ice mitigation strategy. Since the present LNG carriers are 45.8 m wide, two icebreakers will be required to escort them. The time spent waiting for icebreaker assistance is drawn from a normal distribution with a mean value of 2 hours and a standard deviation of 1 hour. The relatively low waiting time was determined on the assumption that the icebreaker service in the area would be adjusted to the demands of the assumed regular service route. The icebreakers are assumed to assist the vessels from the first to the last waypoint along the route where the ice thickness exceeds the determined maximum value for independent operation. The average speed of the icebreakers and the assisted vessel is assumed to be 8 kn. Figure 8 shows an example of how the speed of a ship that operates in up to 1.2 m thick ice is affected by icebreaker assistance when the ice thickness exceeds 1.2 m.

The number of days of icebreaker assistance required for the whole fleet of 6 vessels for various ice scenarios and ice mitigation strategies is shown in Table 3.

Table 3: Required icebreaker assistance in days for various ice scenarios and ice classes (for the whole fleet of LNG carriers).

	Ice scenario 1			Ice scenario 2		
Year	PC 7	PC 5	PC4	PC 7	PC 5	PC4
2016	521	198	0	438	110	0
2017	523	185	0	433	104	0
2018	560	238	5	424	100	0
2019	541	220	1	492	175	0
2020	582	257	8	403	61	0
2021	554	231	2	428	97	0
2022	523	191	0	456	125	0
2023	597	273	21	441	111	0
2024	610	278	58	296	0	0
2025	636	316	133	421	97	0
Total	5647	2385	227	4233	979	0
	Ice scenario 3			Ice scenario 4		
Year	PC 7	PC 5	PC 4	PC 7	PC 5	PC4
2016	427	101	0	469	153	0
2017	395	46	0	424	98	0
2018	405	58	0	424	99	0
2019	378	22	0	409	61	0
2020	289	0	0	488	164	0
2021	317	0	0	557	231	3
2022	298	0	0	439	107	0
2023	301	0	0	437	104	0
2024	130	0	0	526	194	0
2025	126	0	0	561	241	4
Total	3065	227	0	4734	1453	8

3.9 *Fuel costs related to the choice of ice mitigation strategy*

Operation in ice-covered water requires large amount of propulsion power to overcome the resistance between the ice and the ship´s hull. A ship built to operate independently in up to 1.7 m of ice requires therefore significantly more propulsion power than a ship built to operate independently in maximum 0.7 m of ice. This is shown in Table 1 that presents propulsion power requirements for vessel with various ice-going capabilities or polar classes.

A larger power requirement results in both higher investment costs and significantly higher fuel consumption as the fuel consumption can be considered directly related to the power demand. Thus, the additional fuel costs related to the PC 5 and PC 4 ships in the present study need to be considered. To this aim, the number of days when the PC 5 and PC 4 vessels need their additional power was determined as shown in Table 4.

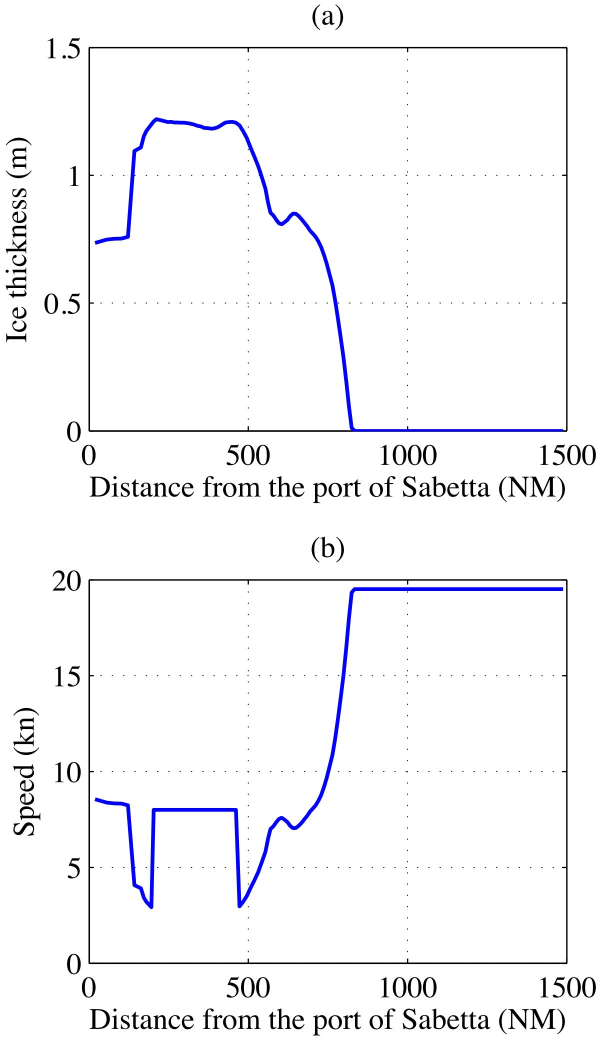

Figure 8. Example of how the speed of a ship that operates independently in up to 1.2 m thick ice is affected by icebreaker assistance when the ice thickness exceeds 1.2 m: (a) The ice thickness along the route; (b) The corresponding speed of the vessel

The PC 5 classified ship is assumed to need its additional power of 57,000 kW - 30,000 kW = 27,000 kW when the ice thickness is larger than 0,7 m and smaller than 1.2 m. The PC 4 vessel is assumed to need the same amount of additional power as the PC 5 ship as long as the ice thickness is less than 1.2 m. When the ice thickness is larger than 1.2 m and less than 1.7 m, the PC 4 ship is assumed to need an additional power of 90,000 kW - 30,000 kW = 60,000 kW. With icebreaker assistance both the PC 5 and the PC 4 vessels are both assumed to have the same power requirement as the PC 7 vessels. Assuming use of HFO as fuel, an average HFO price of USD 750 per ton, and a specific fuel consumption of 180 g/kWh, the additional fuel cost for a fleet of PC 5 vessels amount to 6 x USD 87,000 per day = USD 524,000 per day (when the additional power is required). The corresponding figure for a fleet of PC 4 vessels is 6 x USD 194,000 = USD 1,166,000.

In the above fuel cost calculation, only the use of HFO as fuel is considered. It should be mentioned that LNG carriers are typically fitted with a so-called dual-fuel engine that can run on either natural gas or HFO. However, currently most LNG carriers use HFO as fuel as it for the moment is cheaper than natural gas. Thus, use of natural gas as fuel with not be further discussed in the present paper.

Table 4: Number of days when the additional power of the PC 5 and PC 4 vessels is needed for various ice scenarios (for the whole fleet of LNG carriers)

PC 5: Number of days when 0.7m <ice thickness < 1.2 m				
IS = Ice Scenario				
Year	IS 1	IS 2	IS 3	IS 4
2016	323	328	326	316
2017	338	330	349	325
2018	322	324	347	325
2019	321	316	356	348
2020	326	342	289	324
2021	323	332	317	325
2022	332	331	298	332
2023	324	330	301	333
2024	332	296	130	332
2025	321	324	126	319
PC 4: Number of days when 1.2m <ice thickness < 1.7 m				
Year	IS 1	IS 2	IS 3	IS 4
2016	198	110	101	153
2017	185	104	46	98
2018	233	100	58	99
2019	219	175	22	61
2020	249	61	0	164
2021	229	97	0	228
2022	191	125	0	107
2023	251	111	0	104
2024	221	0	0	194
2025	183	97	0	237

3.10 *Comparison of ice mitigation related costs for the various ice mitigation strategies*

To enable a holistic comparison of the various ice mitigation strategies, the Net Present Cost (NPC) of all their related costs were calculated. All costs except the additional investment costs related to the PC 5 and PC 4 vessels were discounted using an assumed interest of 8 %. The obtained NPC values are presented in Table 5.

The figures presented in Table 5 indicate clearly that ice mitigation strategy 1 with PC 7 vessels is the most economical alternative for all ice scenarios. However, the outcome is quite sensitive to the assumed costs for icebreaker assistance. Assuming that the two icebreaker required to escort one of the LNG carriers would cost USD 80,000 x 2 = USD 160,000 or more per day instead of the USD 50,000 x 2 = USD 100,000, ice mitigation strategy 2 with PC 5 built ships would be more economical.

Table 5: NPC of ice mitigation costs for various ice scenarios and ice mitigation strategies

IS 1	**PC 7**	**PC 5**	**PC 4**
IB support (days)	5,647	2,385	227
Addl. fuel cons. (t)	0	380,000	940,000
NPC (USD)	3.7E+08	5.1E+08	8.8E+08
IS 2	**PC 7**	**PC 5**	**PC 4**
IB support (days)	4,233	979	0
Addl. fuel cons. (t)	0	380,000	633,000
NPC (USD)	2.9E+08	4.2E+08	7.2E+08
IS 3	**PC 7**	**PC 5**	**PC 4**
IB support (days)	3,065	227	0
Addl. fuel cons. (t)	0	331,000	390,000
NPC (USD)	2.2E+08	3.5E+08	6.1E+08
IS 4	**PC 7**	**PC 5**	**PC 4**
IB support (days)	4,734	1,453	8
Addl. fuel cons. (t)	0	383,000	757,000
NPC (USD)	3.1E+08	4.4E+08	7.7E+08

4 CONCLUSIONS

The present study resulted in an approach towards the design of robust arctic maritime transport systems that are able to deal with various possible future ice scenarios. It makes it possible to assess how a complex arctic maritime transport system, consisting of a single or multiple vessels, with or without icebreaker assistance, is able to cope with various possible future ice scenarios.

A case study was carried out to demonstrate how the approach could be applied in practice. The outcome from the case study indicates clearly that it, for the investigated route, is more economical to use vessels with a low or medium level ice going capabilities in combination with icebreaker assistance instead of vessels with high ice going capability and a minimum demand for icebreaker assistance. In other words, the results indicate that costs related to higher ice going capabilities are high in comparison with the costs for icebreaker assistance. Especially in case of decreasing ice conditions, the transport system with PC 4 vessels performed poorly while the utilization of the vessels ice going capabilities was limited to the start of the 10-year period, and resulted only in additional capital costs and operating costs towards the end of the period. In reality the PC 4 vessels would most likely perform even worse in comparison with the vessels with lower ice classes as their additional weight would significantly harm their fuel consumption in all ice conditions including open water.

The presented approach can be further developed as its components can easily be modified or replaced for improved accuracy. Components that should be improved include for instance the method for calculation of differences in fuel costs between ships with various ice going capabilities as well as the applied ice data, which should be extended to include openings, ridges, etc.

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ABBREVIATIONS

LNG	Liquefied Natural Gas (LNG)
IB	Icebreaker
IS	Ice Scenario Liquefied
NM	Nautical Mile
NPC	Net Present Costs
PC	Polar Class
USD	United States Dollars

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