POAC'23
Glasgow, United Kingdom

Proceedings of the 27th International Conference on
Port and Ocean Engineering under Arctic Conditions
12-16 June 2023, Glasgow, United Kingdom

The impact of ice classing and ice conditions on the economics of Arctic shipping

Gleb Sibul[1], Peter Schütz[1]

[1] Department of Industrial Economics and Technology Management, Norwegian University of Science and Technology, Trondheim, Norway

ABSTRACT

This article analyzes how ice conditions and the ice class of the vessel affect its optimal route choice and the corresponding operating costs. We use the Northern Sea Route as a case and estimate voyage costs for every ice class for every summer navigation for 40 years. These results consider such features of vessel ice classing as the ability of ice-going vessels to operate at higher speeds and save time using shorter north routes, the necessity of using an icebreaker escort and paying for this service, and fuel consumption differences. We consider the current NSR regulations and different fuel price scenarios. The problem is addressed in two stages. First, we find optimal routes for vessels of different ice classes based on historical satellite ice data between 1980 and 2020 and the polar operational limit assessment risk indexing system (POLARIS) to obtain safe sailing speeds from the ice data. The objective function minimizes total travel time, which includes an icebreaker escort time penalty if a vessel cannot sail at safe operating speed on its own. We analyze how the optimal routes develop over time. Then, the routing data is used as input for cost analysis. Our results provide valuable insights and prove the potential cost-saving potential of ice-protected vessels when navigating in the Arctic.

KEYWORDS

Arctic Shipping; Weather Routing; Ice Routing; Ice Class; Icebreaker.

INTRODUCTION

The Arctic region is one of the most challenging environments for shipping operations. Despite the potential for increased maritime activity due to the melting of sea ice, Arctic shipping is still fraught with risks and uncertainties. As representatives of shipping companies note, high environmental risks reduce the attractiveness of the Arctic routes (Lasserre et al., 2016). Many studies evaluate the prospects for using the Northern Sea Route (NSR) as an international transport corridor. Most studies compare the cost of either sailing through the NSR or the Suez Canal (SCR). Researchers mention that operations along the NSR depend on ice conditions, but still consider model parameters that depend on the ice conditions and the vessel's ice class, such as voyage length and vessel speed, to be constant (Furuichi and Otsuka, 2015; Wan et al., 2018).

Recent studies have extended the cost comparisons by including ice conditions along the NSR. For example, Faury and Cariou (2016) and Cariou et al. (2019) analyze ice thickness data from the Copernicus database and determine the vessel's speed based on that. Faury et al. (2020) analyze the effect of ice thickness and develop a profit-decision model, considering the effect of global warming. Sibul and Jin (2021) develop an economic model for the strategic assessment of the Arctic routes. It is tailored to the NSR and considers the effect of an ice class on ship purchasing price and an icebreaker escort fee following the NSR regulations.

Vessel's route in the Arctic is usually defined by ice conditions (Kotovirta et al. 2009). Some authors try to develop weather-routing algorithms to find an optimal route in terms of travel time, safety, cost, or propulsion performance. They connect weather data with vessel characteristics such as sailing speed, creating a 'transit model' (Kotovirta et al. 2009; Nam et al. 2013; Choi et al., 2015). Particularly, authors use the Arctic Ice Regime Shipping System (AIRSS Canada) to calculate the relative risk in different ice conditions depending on the vessel's ice class (Sibul et al., 2022). It is the accepted methodology to determine a set of operational limitations in ice. Later, this methodology was incorporated into Polar Operational Limit Assessment Risk Indexing System (POLARIS; IMO, 2016). For example, Zhang et al. (2017) use AIRSS and a path-finding algorithm for ice route planning and validate it using the ice condition data from Yong Sheng transit trip via the NSR. Li et al. (2019) develop a voyage planning tool for ships sailing between Europe and Asia, considering ice data based on POLARIS and other environmental parameters. Bergström et al. (2022) suggest using a comprehensive approach for risk management in the Arctic. They propose adding an additional term into the current POLARIS methodology that reflects the magnitude of potential consequences. The most dangerous is the risk of a ship becoming beset in ice. Vanhatalo et al. (2021) propose a Bayesian method of estimating the probability of a vessel becoming beset in ice in the NSR based on AIS and ice data. One of the most severe environmental risks is an accidental oil spill (Bambulyak and Ehlers, 2020). Bergström et al. (2022) argue that other parameters are also important: life-threatening risks and socioeconomic indicators.

In this paper, we evaluate how voyage operational expenses (VOYEX) for the NSR depend on the vessel's ice class and the ice conditions along the NSR. We define VOYEX as the sum of fuel and carbon costs, insurance costs, crew costs, tariff costs, and port dues. It should be noted, our VOYEX is different from the classical voyage expenditures since we also include crew and insurance costs (Stopford, 2008). The problem is addressed in two stages. In the first one, we find optimal routes for vessels of different ice classes, using 1980-2020 satellite ice data from Global Ice-Ocean Modeling and Assimilation System (GIOMAS; Zhang and Rothrock, 2003) and the POLARIS method. The output of this stage is sailing distance, travel time, average sailing speed for different ice classes, and the necessity of an icebreaker escort for specific route segments (NSR zones). In the second stage, the optimal route data is used as input for cost analysis. We consider the current summer navigational window of five months and estimate VOYEX for vessels of different ice classes. We consider the NSR regulations and use three fuel prices and two carbon tax scenarios.

METHODOLOGY

We start by presenting the cost model and explaining the different VOYEX components. Then, we show how sailing speed is estimated based on POLARIS and available ice data for every ice class. Higher sailing speed and softened ice conditions allow making more voyages, which generally decreases voyage operating costs. Finally, we present the optimization model used to determine the optimal routes for the different ice classes based on the ice data using POLARIS.

These optimal routes are the basis for estimating VOYEX. According to current NSR regulations, the summer navigation period lasts for five months, starting on 1st July and ending on 30th November (NSRA rules). The number of voyages via NSR is increasing, yet there are only a few dozen of transit trips per year (Özcan et al., 2022). These transit voyages usually pass through the territorial waters of the Russian Federation without entering intermediate ports. Some route segments such as the East Siberian Sea and Laptev strait are shallow. Pruyn (2016) notes a draft restriction of 12.5 m. That is why we consider a General Cargo Handysize vessel with a gross registered tonnage of 24000 tons, using the information on China Ocean Shipping Company vessels that sailed the NSR (Sibul and Jin, 2021). The origin and destination ports are Shanghai and Rotterdam since they are the busiest ones in Asia and Europe.

Cost Estimation

We estimate VOYEX for vessels of different ice classes under different ice scenarios that are represented by data between 1980 and 2020. We consider a ship suitable for shipping via the NSR and use origin and destination ports, where it is easy to find cargo to load the ship fully. Note that capital and maintenance costs are not included, as we focus on operating an existing fleet of vessels. VOYEX is estimated as:

$$VOYEX = Fuel + Carbon + Icebreaker\ escort + Insurance + Port + Crew \tag{1}$$

Fuel and carbon tax

Fuel is the largest cost component, and subject to considerable fluctuations. We therefore consider three levels of oil price: 250, 500, and 750 USD per ton. Additionally, we consider the carbon tax of 60 or 120 USD per ton of CO_2. The first value corresponds to the current average carbon tax in Europe, while the second represents the carbon tax in the 2030s (OECD, 2021). Each ton of heavy fuel oil emits 3.114 tons of CO_2 (IMO, 2009). The total fuel consumption per voyage is calculated as:

$$f_{tot} = \left(k_1 \cdot v_{avg}^3 + k_2\right) \cdot t_{avg} \cdot f_{incr} + 2 \cdot f_{port} \tag{2}$$

where

k_1 and k_2 – coefficients for a vessel's size (see Yao et al., 2011),

v_{avg} and t_{avg} – average sailing speed and sailing time for a vessel given ice class and year during the summer navigation,

f_{incr} – fuel consumption increment for an ice class i (Sibul and Jin, 2021),

f_{port} – fuel consumption in port, 10 tons per day.

Tariff cost

According to the NSR rules, if a vessel needs icebreaker support in a particular route arc, it has to pay for it for the entire zone (Sibul et al., 2022). Knowing that the NSR fee is paid in rubles we also consider the USD/RUB exchange rate. We assume it to be 75 rubles per US dollar (2021 average value). The NSR icebreaker escort tariff per voyage is estimated as follows:

$$c_{tariff} = \frac{n_{NSR} \cdot GRT \cdot tariff(n_z)}{rate} \tag{3}$$

where

n_z – the number of NSR zones a vessel of ice class i requires an escort,

GRT – vessel's gross registered tonnage, 24000 tons,

$tariff(n_z)$ – NSR tariff of ice class i per unit of GRT (NSRA tariffs),

$rate$ – USD to RUB exchange rate.

Insurance

The insurance cost depends on a large number of factors. As there is little experience from Arctic transits, voyages are usually assessed individually. Schøyen and Bråthen (2011) contacted an insurance company to obtain the insurance cost for an Arc 4 vessel. As noted by Fedi et al. (2018), insurance cost increases as risk increases (and vice versa). Vessels of higher ice class are usually subject to lower risk but may sail in harsher, i.e. riskier, ice conditions. The influence of these factors is difficult to estimate. We therefore use an insurance cost of 125000 USD per voyage, irrespective of route and ice class.

Port and crew costs

Our model includes one port call per voyage. Port call duration is assumed to be two days (UNCTAD Review of Marine Transport, 2019). A port due is 18000 USD. Crew costs include a premium for the Arctic sailing experience and are 200000 USD per month (Wan et al., 2018).

Speed Estimation

Speed is estimated using the POLARIS method (IMO, 2016). To determine vessel ice navigability, one needs to know its ice class, ice type (ice thickness), and ice concentration. Each ice class has its ice risk indices. We use the Russian ice classes since they are connected with ice breaker escort tariffs (Russian Maritime Register of Shipping, Table 1).

Table 1. Risk index values (RIV) for Russian ice classes (IMO, 2016)

Ice class		Ice type and ice thickness, cm											
RMRS[1]	IACS[2] FSICR[3]	OW	NI	G	GW	FY1	FY2	MFY1	MFY2	TFY1	TFY2	SY	MY
		—	0-10	15-10	15-30	30-50	50-70	70-90	90-120	120-180	180-250	250-300	300-400
—	PC1	3	3	3	3	2	2	2	2	2	2	1	1
—	PC2	3	3	3	3	2	2	2	2	2	1	1	0
Arc9	PC3	3	3	3	3	2	2	2	2	2	1	0	-1
Arc8	PC4	3	3	3	3	2	2	2	2	1	0	-1	-2
Arc7	PC5	3	3	3	3	2	2	1	1	0	-1	-2	-2
Arc6	PC6	3	2	2	2	2	1	1	0	-1	-2	-3	-3
Arc5	PC7	3	2	2	2	1	1	0	-1	-2	-3	-3	-3
Arc4	IAS	3	2	2	2	2	1	0	-1	-3	-3	-4	-4
Ice3	IA	3	2	2	2	1	0	-1	-2	-3	-4	-5	-5
Ice2	IB	3	2	2	1	0	-1	-2	-3	-4	-5	-6	-6
Ice1	IC	3	2	1	0	-1	-2	-3	-4	-5	-6	-7	-8
No ice class		3	1	0	-1	-2	-3	-4	-5	-6	-7	-8	-8

[1]RMRS – Russian Maritime Register of Shipping, [2]IACS – International Association of Classification Societies, [3]FSICR – Finnish-Swedish Ice Class Rules

Knowing the ice concentration at each node $cice_{xy}$, ice thickness $hice_{xy}$ from the ice data, the risk index outcome RIO_{xyc} for ice class *c* is calculated as:

$$RIO_{xyc} = 10 \cdot \left(cice_{xy} \cdot RIV_{xyc}(hice_{xy}) + (1 - cice_{xy}) \cdot RIVW_{xyc}(hice_{xy})\right) \quad (4)$$

where

$hice_{xy}$ – ice thickness at node N_{xy},

$cice_{xy}$ – ice concentration at node N_{xy},

RIV_{xyc} – risk index value for ice class *c* for ice thickness and ice concentration at node at node N_{xy} (Table 1),

$RIVW_{xyc}$ – risk index value for open water at node N_{xy} for ice class *c* (Table 1).

We use ice thickness and ice concentration data from GIOMAS (Zhang and Rothrock, 2003). It is averaged monthly data saved in the global curvilinear coordinate system every month between 1980 and 2020. POLARIS assumes the presence of several ice types in the ice pilot visibility zone, and their ice numerals are summed up. Since we use ice data from satellite observations of relatively low resolution, ice type and ice concentration are the same within one node. Then, we are left with two terms (for ice water and open water). If the ice numeral is positive, we assign the ship a safe speed according to Table 2. If not, the arc is considered escorted, and a ship is assigned a speed based on ice-breaker RIO, using ice class Arc9.

Table 2. Ship's speed based on risk index outcome (Stephenson et al, 2013; McCallum, 1996)

RIO	Speed, kt
< 0	requires escort
0-8	4
9-13	5
14-15	6
16	7
17	8
18	9
19	10
20	11
> 20	15 (base speed)

Determining Optimal Routes

Sailing through areas with severe ice conditions requires considerable speed reduction. So, we find the optimal route to be the one that minimizes travel time. Let us consider a directed graph $G = (N, A)$ with the set of nodes *N* and the set of arcs *A*. A standard integer programming formulation to determine a shortest path from node *s* to node *t* is the following:

$$min \sum_{i \in A} \sum_{j \in A} t_{ij} x_{ij} \quad (5)$$

subject to

$$\sum x_{ij} - \sum x_{ji} = \begin{cases} 1, & s = t \\ -1, & i = t \\ 0, & n \neq s, t \end{cases} \quad (6)$$

$$x_{ij} \in \{0, 1\} \; \forall \; (i, j) \in A \quad (7)$$

where $t_{ij} \in R$ are the arc traveling time, x_{ij} are binary arc variables that take value 1 if the arc $a(i,j)$ belongs to the path. Constraint (6) is a flow conservation constraint, which implies the source node *s* has only one leaving arc, the target node *t* has only one entering arc, and all intermediate nodes have both leaving arc and entering arc. Travel time between two consecutive nodes t_{ij} is defined as follows:

$$t_{ij} = \frac{d_{ij}}{v_{ij}} \tag{8}$$

where d_{ij} is the shortest surface distance between two adjacent nodes *i* and *j* on the elliptical earth model, v_i is a vessel speed between these nodes.

Speed v_i is the most important parameter in our model. It is calculated using the POLARIS method and it depends on ice conditions in the node and a vessel's ice class:

$$v_{ij} = \begin{cases} v_o, & RIO > 20 \\ v_{ice}, & 20 \geq RIO \geq 0 \\ v_{esc}, & RIO < 0 \end{cases} \tag{9}$$

According to (9), we consider three main sailing conditions. First, If RIO is more than 20, a ship sails at its base cruising speed, which implies normal operations and usually happens in ice-free waters. The second condition (*20≥RIO≥0*) is mainly represented by ice waters, where a ship sails with elevated operational risk and has to reduce its speed (see Table 2). Third, a vessel requires escort when RIO is negative. In that case, the ice class is set to the maximum, the speed is calculated based on icebreaker ice class (Arc9), but the arc is considered as escorted.

Finally, we solve the optimization problem using the A* as an algorithm for finding the shortest path (Hart et al., 1968). We estimate route parameters such as sailing speed, distance, time, the icebreaker escort necessity, and the number of escorted zones. Later, they are used for voyage operating cost estimation.

RESULTS AND DISCUSSION

We first find optimal shipping routes for every month of summer navigation between 1980 and 2020 for every ice class. Second, we average this data for every summer navigation period and compared VOYEX for various fuel prices and carbon taxes. We consider nine ice classes, Shanghai – Rotterdam O-D pair, and the most suitable ship size and cargo type for use in the NSR.

Optimal Routes Analysis

We start with the analysis of the different optimal routes for the different ice classes. Examples for optimal routes for three different ice classes in September 1980 and September 2020 are shown in Figure 1. Generally, a higher ice class means that a ship can sail further north in order to save time (note that the projection in Figure 1 misrepresents the true length of a route). Ships without or with a low ice class usually sail closer to the coast as ice is often thinner there. Still, the routing results are highly dependent on ice conditions and may change considerably from year to year. Overall, vessels can make from one to six voyages during 153 days of the navigation period depending on their ice class.

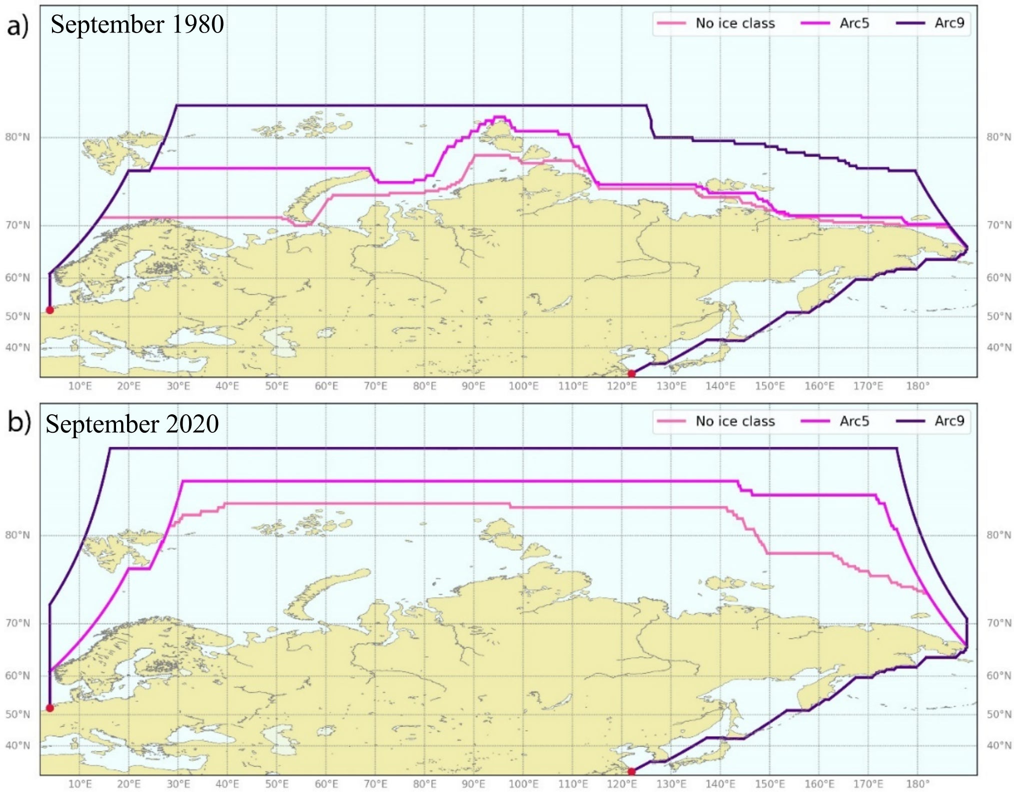

Figure 1. Examples of optimal routes

Figures 2b and 2c illustrate average sailing time and speed. Vessels without ice protection and Ice1 vessels stand out in the figures. According to POLARIS, they have low RIO and, respectively, low sailing speeds and large voyage times. Surprisingly, the routing data for ships without ice preparation contradicts the overall trend of ice conditions softening. Based on the results, their sailing times increase, while speeds decrease. According to our model, a vessel calls for an icebreaker escort, only if it cannot sail on its own, that is, if the risk index outcome is negative. It implies ships without ice protection also seek to try to sail further north, decreasing the level of an icebreaker escort at the same time. Figure 2d illustrates the average number of zones where the escort is mandatory. It can be seen that the number of zones with required icebreaker escort falls drastically throughout the study period.

It should be noted that routing decisions are solely based on the POLARIS method. It is used widely, but we believe the dependency between risk index outcome and safe operation speed should be validated and/or calibrated based on the real AIS data for the Arctic ice conditions. Unfortunately, this data is difficult to obtain since sailing experience in the Arctic is limited, and the data itself might not be publicly available.

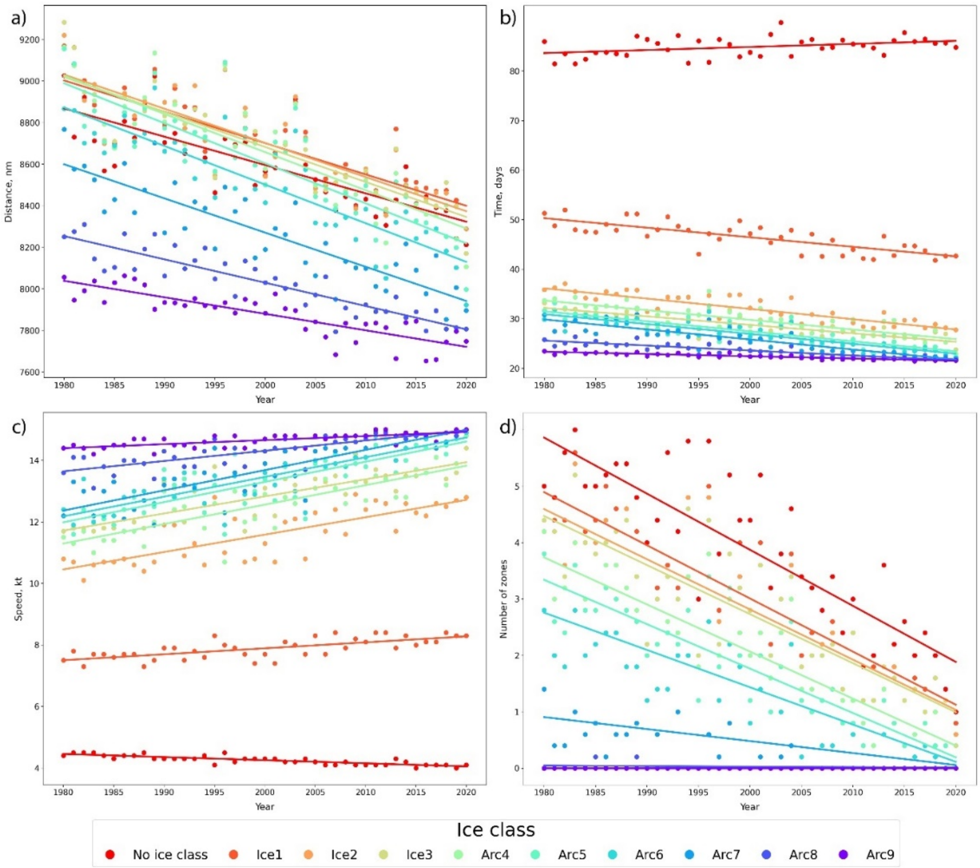

Figure 2. Average NSR route parameters during summer navigation:
a) distance, b) time, c) speed, d) number of zones with icebreaker support

Cost Analysis

Ice conditions and ice class have a direct influence on transportation costs. We also evaluate how they change given global warming trend, various ice classes, and fuel prices. First, we analyzed how VOYEX changes with time (Figure 3a). For our base scenario, we use a fuel price of 500 USD per ton, and a carbon tax of 60 USD per ton of CO_2 since both are close to the current price levels. Not surprisingly, we see a downward trend here. However, it is pretty slow because the main driver of price – the number of voyages – cannot change rapidly.

Second, we analyze how fuel prices affect VOYEX given 2020 ice data (Figure 3b). For every scenario, VOYEX decreases as ice class increases. The main driver behind this is the fact the higher ice class vessels can sail faster and make more voyages. They also reduce costs through independent navigation, which exempts them from paying the NSR icebreaker tariff. In our model, ice classes Arc8 and Arc9 can make five or six voyages during the summer navigation. On the contrary, a vessel without ice preparation can make only one voyage since it is forced to sail independently and assigned a low speed by POLARIS. What is important, we can see VOYEX considerably decreases between vessels without ice class and Ice3, and then ice classing has almost no influence on cost. It means that investment in ice classes higher than Ice3 makes no difference for summer navigation, especially considering that our model neglects capital and maintenance costs. Despite fuel price significantly affecting the costs, it holds for every fuel price scenario.

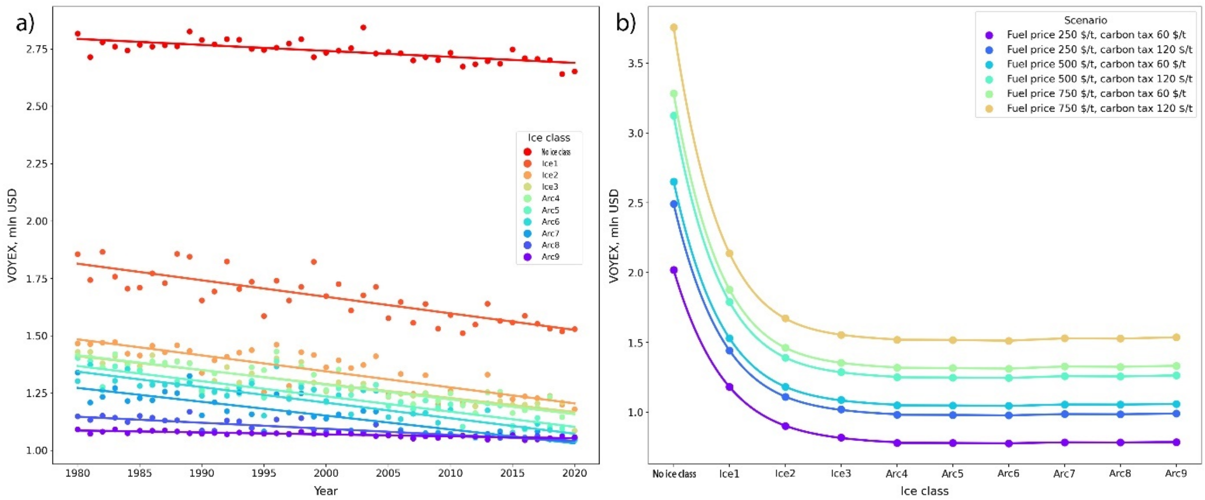

Figure 3. a) NSR voyage costs during the summer navigation for the base scenario, b) sensitivity analysis for different fuel prices

It is important to note that our cost model is tailored for the NSR. We assume the most relevant vessel and cargo type for this route. We also used the busiest origin and destination ports, Shanghai and Rotterdam, expecting it facilitates maximizing the load rate. However, this parameter is one of the key factors determining the profitability of such a niche route as the NSR. We also suppose we already have an ice-going vessel and want to use all benefits of a summer NSR navigation. It implies that we assess short-term ship cost-effectiveness. For example, Bergström et al. (2016) show that for certain operations, using ships of a lower ice class assisted by an icebreaker may be more cost-effective than using higher ice class ships. They usually suffer from higher capital and fuel costs whenever they cannot utilize their higher ice class, e.g., in open waters or light ice during summer navigation or in port.

CONCLUSION

This paper examines the effects of ice conditions and the ice class of a vessel on its optimal route choice and the corresponding voyage costs. Using historical satellite ice data between 1980 and 2020 and the polar operational limit assessment risk indexing system (POLARIS) we estimate voyage costs for the Northern Sea Route for every ice class for each summer navigation period for 40 years, considering different fuel prices and carbon tax scenarios. Our findings suggest that higher ice classes can save time sailing further north and operate at higher speeds, which largely diminishes the necessity of an icebreaker escort, as well as the associated cost. Furthermore, the results of our analysis reveal that a vessel's ice class has a significant impact on the total voyage operating costs, with the most significant difference occurring between ships without ice class and Ice3. After that, investing in ice classes higher than Ice3 makes almost no difference for summer navigation, particularly considering that our model neglected capital and maintenance costs. As for future research, we plan to consider the ice data uncertainty and deal with that using a stochastic formulation of the routing problem. We plan to use not only past ice data but also future predictions. We believe it allows to get input data for solving other optimization problems relevant to future shipping activities in the Arctic, such as vessel routing and scheduling, ice-going fleet deployment, ice-going fleet size and mix, and others.

REFERENCES

Arctic Ice Regime Shipping System (AIRSS) Standard. Accessed 1 March 2023. https://tc.canada.ca/en/marine-transportation/marine-safety/tp-12259e-arctic-ice-regime-shipping-system-airss-standard.

Bambulyak, A. and Ehlers, S., 2020. Oil spill damage: a collision scenario and financial liability estimations for the Northern Sea Route area. Ship technology research, 67(3), pp.148-164.

Bergström, M., Erikstad, S.O., Ehlers, S., 2016. A simulation-based probabilistic design method for arctic sea transport systems. J. Marine. Sci. Appl. 15, 349–369.

Bergström, M., Browne, T., Ehlers, S., Helle, I., Herrnring, H., Khan, F., Kubiczek, J., Kujala, P., Kõrgesaar, M., Leira, B.J. and Parviainen, T., 2022. A comprehensive approach to scenario-based risk management for Arctic waters. Ship technology research, 69(3), pp.129-157.

Cariou, P., Cheaitou, A., Faury, O. and Hamdan, S., 2021. The feasibility of Arctic container shipping: the economic and environmental impacts of ice thickness. Maritime Economics & Logistics, 23, pp.615-631.

Choi, M., Chung, H., Yamaguchi, H. and Nagakawa, K., 2015. Arctic sea route path planning based on an uncertain ice prediction model. Cold Regions Science and Technology, 109, pp.61-69.

Faury, O. and Cariou, P., 2016. The Northern Sea Route competitiveness for oil tankers. Transportation Research Part A: Policy and Practice, 94, pp.461-469.

Faury, O., Cheaitou, A. and Givry, P., 2020. Best maritime transportation option for the Arctic crude oil: A profit decision model. Transportation Research Part E: Logistics and Transportation Review, 136, p.101865.

Fedi, L., Faury, O. and Gritsenko, D., 2018. The impact of the Polar Code on risk mitigation in Arctic waters: a "toolbox" for underwriters? Maritime Policy & Management, 45(4), pp.478-494.

Furuichi, M. and Otsuka, N., 2015. Proposing a common platform of shipping cost analysis of the Northern Sea Route and the Suez Canal Route. Maritime Economics & Logistics, 17, pp.9-31.

Hart, P.E., Nilsson, N.J. and Raphael, B., 1968. A formal basis for the heuristic determination of minimum cost paths. IEEE transactions on Systems Science and Cybernetics, 4(2), pp.100-107.

International Maritime Organization. (2009). Guidelines for voluntary use of the ship energy efficiency operational indicator (EEOI). IMO. Accessed 7 February 2023. https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/Circ-684.pdf

Kotovirta, V., Jalonen, R., Axell, L., Riska, K. and Berglund, R., 2009. A system for route optimization in ice-covered waters. Cold Regions Science and Technology, 55(1), pp.52-62.

Lasserre, F., 2014. Case studies of shipping along Arctic routes. Analysis and profitability perspectives for the container sector. Transportation Research Part A: Policy and Practice, 66, pp.144-161.

Lasserre, F., Beveridge, L., Fournier, M., Têtu, P.L. and Huang, L., 2016. Polar seaways? Maritime transport in the Arctic: An analysis of shipowners' intentions II. Journal of Transport Geography, 57.

Li, Z., Ringsberg, J.W. and Rita, F., 2020. A voyage planning tool for ships sailing between Europe and Asia via the Arctic. Ships and Offshore Structures, 15(sup1), pp.S10-S19.

McCallum, J., 1996. Safe speed in ice: an analysis of transit speed and ice decision numerals. Ship Safety Northern (AMNS).

Guidance on methodologies for assessing operational capabilities and limitations in ice. Tech. Rep. MSC. 1/Circ. 1519, International Maritime Organization (IMO), London. 2016. Accessed 1 March 2023. https://www.nautinst.org/uploads/assets/uploaded/2f01665c-04f7-4488-802552e5b5db62d9. pdf.

Nam, J.H., Park, I., Lee, H.J., Kwon, M.O., Choi, K. and Seo, Y.K., 2013. Simulation of optimal arctic routes using a numerical sea ice model based on an ice-coupled ocean circulation method. International Journal of Naval Architecture and Ocean Engineering, 5(2), pp.210-226.

Northern Sea Route Administration. Rules of navigation in the Northern Sea Route. Accessed 1 March 2023. http://www.nsra.ru/en/ofitsialnaya_informatsiya/pravila_plavaniya.html

Northern Sea Route Administration. Tariffs for the Icebreaker Escorting of Ships Rendered by FSUE «Atomflot» in the Water Area of the Northern Sea Route. Accessed 3 March 2023. http://www.nsra.ru/en/ofitsialnaya_informatsiya/tarrifs_for_icebreaker_escort_atomflot.html

OECD, 2021. Effective Carbon Rates 2021 Pricing Carbon Emissions Through Taxes and Emissions Trading. OECD Publishing.

Özcan, E., Yirmibeşoğlu, S. and Özsoy, B., Examining the Maritime Activities and Environmental Effects of The Ice Class Ships.

Pruyn, J.F., 2016. Will the Northern Sea Route ever be a viable alternative? Maritime Policy & Management, 43(6), pp.661-675.

Schøyen, H. and Bråthen, S., 2011. The Northern Sea Route versus the Suez Canal: cases from bulk shipping. Journal of Transport Geography, 19(4), pp.977-983.

Sibul, G. and Jin, J.G., 2021. Evaluating the feasibility of combined use of the Northern Sea Route and the Suez Canal Route considering ice parameters. Transportation Research Part A: Policy and Practice, 147, pp.350-369.

Sibul, G., Yang, P., Muravev, D., Jin, J.G. and Kong, L., 2022. Revealing the true navigability of the Northern Sea Route from ice conditions and weather observations. Maritime Policy & Management, pp.1-17.

Smith, L.C. and Stephenson, S.R., 2013. New Trans-Arctic shipping routes navigable by midcentury. Proceedings of the National Academy of Sciences, 110(13), pp.E1191-E1195.

Stopford, M., 2008. Maritime economics 3e. Routledge.

UNCTAD – United Nations Conference on Trade and Development, 2019. Review of Maritime Transport 2019. United Nations Publications, New York. Accessed 12 February 2023. https://unctad.org/system/files/official-document/rmt2019_en.pdf.

Vanhatalo, J., Huuhtanen, J., Bergström, M., Helle, I., Mäkinen, J. and Kujala, P., 2021. Probability of a ship becoming beset in ice along the Northern Sea Route–a Bayesian analysis of real-life data. Cold Regions Science and Technology, 184, p.103238.

Wan, Z., Ge, J. and Chen, J., 2018. Energy-saving potential and an economic feasibility analysis for an Arctic route between Shanghai and Rotterdam: Case study from China's largest container sea freight operator. Sustainability, 10(4), p.921.

Yao, Z., Ng, S.H. and Lee, L.H., 2012. A study on bunker fuel management for the shipping liner services. Computers & Operations Research, 39(5), pp.1160-1172.

Zhang, J. and Rothrock, D.A., 2003. Modeling global sea ice with a thickness and enthalpy distribution model in generalized curvilinear coordinates. Monthly Weather Review, 131(5), pp.845-861.