ORIGINAL ARTICLE

The feasibility of Arctic container shipping: the economic and environmental impacts of ice thickness

Pierre Cariou[1] · Ali Cheaitou[2] · Olivier Faury[3] · Sadeque Hamdan[2]

Abstract

An evaluation of the competitiveness of the Northern Sea Route (NSR) for container shipping services, considering ice thickness changes during the year, is presented in the present work. The variation in ice thickness has three implications. Firstly, it entails a probability of blockage in ice and reduces the number of days in which a round-trip liner service can be completed. Secondly, ice thickness impacts schedule integrity. Thirdly, it impacts costs (icebreaker fees and fuel consumption), transit time, and the amount of CO_2 emitted per TEU. Accounting for these elements in a model and then in a business case, this study concludes that NSR liner services are only competitive, compared with the Suez Canal Route or the Trans-Siberian Railway Connection, for a limited period of 1.5 months per year.

Keywords Northern Sea Route · Trans-Siberian Railways · Suez Canal Route · Cost · CO_2 emissions

1 Introduction

The Northern Sea Route (NSR) is ice free approximatively 3 months per year (Melia et al. 2016; Stephenson et al. 2014). However, to date, liner shipping services have not been deployed, despite recent trials by major liner shipping companies such as Maersk Line, Cosco, or NYK. In the present work, the reasons why containerships are not using the NSR, despite 40% distance savings, are investigated. The focus of this study is on the ice conditions which are not compatible with the features of liner

✉ Pierre Cariou
  pierre.cariou@kedgebs.com

[1] KEDGE Supply Chain Center of Excellence, KEDGE Business School, 680 Cours de la Libération, 33000 Talence, France

[2] Industrial Engineering and Engineering Management Department, College of Engineering, University of Sharjah, 27272 Shariqah, United Arab Emirates

[3] EM Normandie, Le Havre, France

shipping services. Ice conditions imply a risk of service disruption and hamper two conditions required to deploy a liner service:

First, it is the necessity to provide round services (loop) or trips with a fixed schedule and transit time. Through analysis of daily ice thickness data reported from 2006 to 2016 for 49 NSR subzones, this study shows that only three trips from Shanghai to Hamburg (return) can be offered within a year without risk of blockage in ice. Furthermore, for these three services, a fixed transit time cannot be guaranteed.

Second, the constraints from ice thickness, in particular the obligation of vessels to sail at speeds far from their design speed, means that savings on fuel consumption and transit time might be lower than expected when compared with the Suez Canal Route (SCR) or Tran-Siberian Railways Connection (TRC). This is illustrated by using three selection criteria: the cost per TEU, the transit time, and the amount of CO_2 emitted per TEU.

The main contribution of this paper is the proposal of a model, reflecting the characteristics of Arctic liner shipping services, and its application to a business case where sailing speed is subject to daily variation in ice thickness level. This differs from earlier research which has mostly focused on the NSR's competitiveness for one transit, subject to specific monthly sailing conditions.

The remainder of this manuscript is organized as follows: Section 2 provides a literature review on container shipping NSR competitiveness. Section 3 presents a model that accounts for liner shipping service characteristics, in the specific context of Arctic shipping, when a change in ice conditions exists along the route. Section 4 presents our findings on the number and characteristics of services that can be deployed within a year when using 1A ice-class containerships, and then, a comparison with the SCR and TRC is attempted. Finally, Sect. 5 summarizes the main findings and discusses some potential extensions.

2 Literature review

The feasibility of sailing through the NSR has been subject to many academic studies. As reported by Theocharis et al. (2018), out of 24 articles published since 2011, 20 focused on liner shipping (20) and included a comparison with the Suez Canal Route (Verny and Grigentin 2009; Liu and Kronbak 2010; Erikstad and Ehlers 2012; Lasserre 2014; Cariou and Faury 2015; Faury and Cariou 2016; Faury and Givry 2017; Meng et al. 2017; Benefyk and Peeta 2018; Yuan et al. 2019; Solakiviet al. 2019; Zhang et al. 2019).

One of the main conclusions of these studies is that, despite the economic savings due to shorter sailing distances (up to 40% compared with the SCR), this did not materialize into a significant number of transits (Verny and Grigentin 2009; Cho 2012; Lasserre 2014; Cariou and Faury 2015; Lee and Kim 2015; Aksenov et al. 2017; Zhu et al. 2018). Many reasons explain such a result.

The risk related to sailing through remote geographical locations, the lack of proximity to markets, access to hinterlands, regional bottlenecks, and port infrastructure are some major reasons (Lirn et al. 2004; Song and Yeo 2004). Zhu

et al. (2018) suggest that the NSR can be a viable option for containerships, but that the environmental costs tend to be higher than on the SCR due to smaller ship sizes and lower load factors. The NSR is impacting northern Asian and European countries, as they benefit more from time and fuel cost savings. A higher impact exists for Southern European ports (Adriatic ports), estimated by Button et al. (2017) at 9%.

Meng et al. (2017) argue that the NSR does not really provide an alternative, due to sea ice, weather, and geographical conditions. Yuan et al. (2019) mention the risks of accident and of operational disruptions compared with the Kra Canal. From a stated preference survey of 204 East Asian transportation decision-makers, Benefyk and Peeta (2018) concluded that forwarding companies, companies with less than 1000 TEUs of transport volume per annum, or shipments of chemical commodities are less likely to use the NSR. Lower freight rates, shorter transit time, and sufficient reliability could however change decision-makers' opinion towards the use of the NSR.

Ice conditions play an important role in understanding the attractiveness of the NSR. First, the Arctic involves some specific ice-related risks that often require the use of ice-class vessels (Solakivi et al. 2018; Fedi et al. 2018; Theocharis et al. 2019), with higher capital and operating costs (Erikstad and Ehlers 2012; Lasserre 2014; Cariou and Faury 2015; Lee and Kim 2015; Faury and Cariou 2016; Zhang et al. 2019). Solakivi et al.'s (2019) investigation on the additional costs of ice imposed on container vessels concluded that the additional daily shipping costs for ice classed vessels in open waters was 1 USD/TEU in summertime and up to 4 USD/TEU in wintertime. Kiiski et al. (2016) argue that, in the longer term, NSR traffic is likely to remain marginal, due to the ageing icebreakers and ice-classed fleets and the lack of a critical mass of cargo, as there are limited ports of call along the route.

Second, voyage costs are also impacted by weather conditions through the speed–fuel consumption relationship (Lasserre 2014; Faury and Cariou 2016; Theocharis et al. 2019) and icebreaker assistance (Gritsenko and Kiiski 2016). Third, despite an increase in the length of the navigation season over the years (Comiso 2012; Stephenson et al. 2014; Lee and Kim 2015; Melia, et al. 2016), variations in daily or monthly ice conditions along the route (Pelletier and Lasserre 2012; Zhang et al. 2019) are still important and impact liner operators that need to set in advance a departure date and a fixed transit time.

When comparing the NSR with the TRC, Verny and Grigentin (2009) and Moon et al. (2015) concluded that railway presented higher competitiveness. The lack of NSR competitiveness has been reinforced by recent projects (Cheng 2016; Zhai 2018) associated with the Belt and Road Initiative (BRI). Psaraftis and Kontovas (2010) stressed a competitive advantage for the Eurasian rail route, given the most expensive cargoes. As underlined by Yang et al. (2018), despite their limited capacity and higher transport costs (Lasserre et al. 2018), railroads offer lower transit times and are not impacted by oil price fluctuations or by new International Maritime Organization (IMO) upcoming rules, such as the global sulfur cap (January 2020). The TRC transit time is always shorter than the NSR (Psaraftis and Kontovas 2010; Lasserre et al. 2018; Yang et al. 2018), while railroad CO_2 emissions are significantly higher than on the SCR (Yang et al. 2018).

To conclude, and in line with Aksenov et al. (2017), sea ice extent, ice thickness, and ice properties (e.g., ice ridging, drift ice, and internal pressure) are the most important factors for the short- to medium-term NSR competitiveness, while ocean circulation, winds, currents, and waves will affect navigation in the future. These parameters are considered in the studies of Liu and Kronbak (2010), Furuichi and Otsuka (2013), Stephenson et al. (2014), Faury and Cariou (2016), Zhang et al. (2019), Theocharis et al. (2019), and Lindstad et al. (2016), who integrated in their analyses the impact of sailing conditions on speed and, therefore, costs and emissions of CO_2 or other non-greenhouse gases. The impact of ice conditions is included in the present model (next section), which considers the characteristics of liner services.

3 The model

The model is for an NSR liner shipping service, where a return trip v from a port of origin in Asia to a port of destination in Europe (westbound, w) and return (eastbound, e) is required, and is scheduled along the NSR. Departure time is on the hour and can be set in a year between the 0th and 8760th hour (365×24). tw_0^v and te_0^v are the departure times for trip v, knowing that, to complete the trip, the vessel sails through r subzones[1] westbound (r_w) or eastbound (r_e), with $r_e = R - r_w + 1$ and $r_w = 1, 2 \ldots R$. For the westbound trip, DW_t^v is the cumulative distance traveled from the first sailing hour until the end of hour t with $t = tw_0^v, \ldots, tw_0^v + TTW_O^v$ (in nautical miles, nm) and where $TTW_O^v = TTW^v$ is the total sailing time in hours. Starting from $DW_t^v = 0$, $\forall t \leq tw_0^v - 1$, the vessel sails during the first hour ($t = tw_0^v$) in subzone $r_w = 1$ at a sailing speed of $SW_t^v = SW_{h=tw_0^v}^{r_w=1}$ and $DW_t^v = SW_{h=tw_0^v}^{r_w=1}$. SW_h^r is the possible sailing speed of the vessel in subzone r and during hour h. The sailing speed is calculated as a function of vessel type and the ice conditions in subzone r and in hour h, and is an input parameter to the model. For any other hour $t \geq tw_0^v + 1$ or $DW_{t-1}^v < DW^R$, the sailing speed is

$$SW_t^v = \begin{cases} SW_{h=t}^{r_w=1} & \text{if} \quad DW_{t-1}^v < DW^1 \\ SW_{h=t}^{r_w=2} & \text{if} \quad DW^1 \leq DW_{t-1}^v < DW^2 \\ \quad \vdots \\ SW_{h=t}^{r_w=R} & \text{if} \quad DW^{R-1} \leq DW_{t-1}^v < DW^R \end{cases} \quad (1)$$

The cumulative traveled distance at the end of any hour $t \geq tw_0^v + 1$ of trip v so that $DW_{t-1}^v < DW^R$ is then

$$DW_t^v = \begin{cases} DW_{t-1}^v + SW_t^v & \text{if } DW_{t-1}^v + SW_t^v \leq DW^R \\ DW^R & \text{if } DW_{t-1}^v + SW_t^v > DW^R \end{cases} \quad (2)$$

---

[1] Each subzone is an area where significant changes in ice conditions may exist during the year.

The cumulative sailing time westbound at the end of hour t of trip v so that $DW_{t-1}^v < DW^R$ is

$$TW_t^v = \begin{cases} t - tw_0^v + 1 & \text{if } DW_{t-1}^v + SW_t^v < DW^R \\ t - tw_0^v + \frac{DW^R - DW_{t-1}^v}{SW_t^v} & \text{if } DW_{t-1}^v + SW_t^v > DW^R \end{cases} \tag{3}$$

The total sailing time westbound of trip v, TTW^v is

$$TTW^v = t - tw_0^v + \frac{DW^R - DW_{t-1}^v}{SW_t^v} \tag{4}$$

The actual sailing start hours of the vessel in each subzone r_w of the westbound part of trip v can then be estimated for the first subzone when $r_w = 1$, $TWS_v^1 = tw_0^v$, while for the other subzones, $TWS_v^{r_w} = t$ and $DW_v^{v} \leq DW^{r_w-1}$ and $DW_t^v > DW^{r_w-1}, \forall r_w \geq 2$. Then, the actual sailing end hour of trip v within any subzone can be calculated as $TWF_v^{r_w} = t$ so that $DW_{t-1}^v < DW^{r_w}$ and $DW_t^v \geq DW^{r_w}$.

For the eastbound leg of trip v [all other eastbound leg related parameters can be calculated in a similar way to their corresponding westbound ones using Eqs. (1)–(4)], the first sailing hour is then

$$te_0^v = tw_0^v + TTW^v + P^w + 1, \tag{5}$$

where P^w is the port time in the westbound part of the trip.

A portion of the trip takes place through the NSR, which means that different ice-related conditions exist and are changing over the various subzones r and over time (hours t). It is assumed that this effect is captured by ice thickness ($IW_d^{r_w}$, $IE_d^{r_e}$ westbound and eastbound in subzone r_w or r_e,, respectively) that applies to each calendar day d of a year. The ice thickness impacts the speed of the vessel and the transit time, and can also lead to a risk of ice blockage that changes with vessel characteristics (ice-class). For each hour h in sailing subzone r_w or r_e, the ice thickness is calculated using $IW_h^{r_w} = IW_d^{r_w}$ and $IE_h^{r_e} = IE_d^{r_e}$ for $d = \frac{h}{24}$. Therefore, given the different values of $IW_h^{r_w}$ and $IE_h^{r_e}$, the value of the ice thickness for each hour t of the westbound and eastbound legs of every trip v., IW_t^v and IE_t^v, can be calculated in a similar way to Eq. (1).

Given the values of IW_t^v are IE_t^v, four different configurations are assumed:

When ice thickness level is less than I_1^C, the route is ice free (or open water conditions) and the vessel sails at design speed. This ice thickness level applicable to a vessel (and the following thresholds) depends on the technical specifications for each type of ice-class vessel and on the pertinent regulations.

When ice thickness is between I_1^C and I_2^C, the vessel has to reduce speed, at a level defined by the ice thickness–speed curve.

When ice thickness is between I_2^C and I_3^C, the vessel has to reduce speed and icebreaker assistance is also required.

When ice thickness is more than I_3^C, the vessel cannot sail and the vessel is blocked in ice.

The ice thickness threshold, I_1^C, I_2^C, and I_3^C, depend on the season (winter/spring or summer/autumn) and on the vessel ice class.

In addition, the ice thickness (I_h^r) to speed (S_h^r) relationship during hour h of subzone r between I_1^C and I_3^C is similar to that of Faury and Cariou (2016) so that:

$$S_h^r = A \times \left(\frac{I_h^r}{100} \right)^B, \tag{6}$$

where A and B are the vessel class-dependent parameters which change with its ice class and can be determined using the vessel design speed and the technical minimum speed. Vessel speed in every hour of the westbound and eastbound legs of trip v (SW_t^v and SE_t^v, respectively) are then determined, and the total transit cost of trip v is defined as

$$C_v = CAPEX_v + OPEX_v + IB_v + B_v, \tag{7}$$

where $CAPEX_v$ and $OPEX_v$ are the total capital and operating costs, respectively, while IB_v is the total icebreaker fee if paid for a trip v. B_v is the total fuel cost per round trip for the main and auxiliary engines. The former (B_v^A) depends on the fuel price and on the daily consumption of the auxiliary engine (F^A), and it does not change with speed, contrary to transit time. For the main engine, the round-trip total fuel cost (B_v^M) is equal to

$$B_v^M = C_b^M \times \left(\frac{DW^R - DW_{TTW_O^v - 1}^v}{SW_{tw_0^v + TTW_O^v}^v} F_{tw_0^v + TTW_O^v}^{MW} + \frac{DE^R - DE_{TTE_O^v - 1}^v}{SE_{te_0^v + TTE_O^v}^v} F_{te_0^v + TTE_O^v}^{ME} + \sum_{t=tw_0^v}^{tw_0^v + TTW_O^v - 1} F_t^{MW} + \sum_{t=te_0^v}^{te_0^v + TTE_O^v - 1} F_t^{ME} \right), \tag{8}$$

where $F_t^{MW} = \left(SFC^{MW} PS^M \right) \left(\frac{SW_t^v}{S^{DS}} \right) \frac{1}{10^6}$. SFC^{MW} is the specific fuel oil consumption of the main engine (in g/kWh) in hour t of the westbound leg of trip v and PS^M is the power of the main engine (in kW), and C_b^M is the fuel price. At low or high speed, as in IMO (2014), it is considered that SFC^{MW} is increasing with $SFC^{MW} = SFC_{ds} \times \left(0.4551 \times (EL^{MW})^2 - 0.71 \times EL^{MW} + 1.28 \right)$ and EL^{MW} the main engine load (in %) equal to $EL^{MW} = \left(\frac{SW_t^v}{S^{DS}} \right)$. According to Man B&W (2018), SFC_{ds} is equal to 170 g/kWh at 70% engine load. Moreover, F_t^{ME}, the specific fuel consumption in hour t of the eastbound leg can be calculated in a similar manner.

In Eq. (8), the first and second parts of the equation, correspond to the sailing time on the last hour of trip v westbound and eastbound, respectively, multiplied by the consumption per hour calculated for that hour. The third and fourth parts correspond to the sum of the consumption of the main engine per hour for each hour of the westbound and eastbound legs, respectively, of trip v up to before the last hour in each direction.

Therefore, changes in ice conditions affect the main fuel consumption in two ways. First, as it impacts the transit time, and second, as engine efficiency is affected by speed.

The transit time and type of fuel are therefore impacting the amount of emissions per pollutant per voyage, which can be estimated for various types of emissions (Lindstad et al. 2016; Zhu et al. 2018). In this paper, the attention was limited to the amount of carbon dioxide (CO_2) emitted, which is obtained by multiplying the total fuel consumption by an emission factor (E_f) which depends on the type of fuel used [heavy fuel oil (HFO) versus marine gasoil (MGO)]. The emission factor is equal to 3.113 kg of CO_2 per ton for HFO 380 cst (Zhu et al. 2018) and is equal to 3.206 for MGO (Yoo 2017).

4 Business case

4.1 Dataset

The application presented in this study concerns a hypothetical container service deployed between Shanghai and Hamburg, with a portion of the trip on the NSR (Fig. 1). The total one-way trip length is 8841 nm and is divided into 49 subzones (Table 1). Each subzone corresponds to a grid of 12.5 square kilometers (Cheaitou et al. 2019), and mean daily ice thickness level was calculated (2006–2016) using data collected from the Copernicus Database Ice Thickness (2018). NSR subroutes are therefore subject to changes in ice thickness on a daily basis.

The service involves a 1A ice-class containership, similar to the MV Maersk Venta (Table 2) that left Vladivostok in mid-August 2018 to reach Bremerhaven in September 22 (Lloyd's List 2018).

4.2 Service characteristics

The model defined in Sect. 3 has been implemented in MATLAB R2014a. Table 3 reports the main results for the three round trips that can be completed without ice blockage when using the mean daily level of ice thickness on the 49 subzones and the characteristics of the 1A vessel (ice thickness threshold). Figure 2 shows the sailing speed in knots and the cumulative sailing time in days for the vessel during the westbound and eastbound voyages.

The impact of ice thickness variations leads to the following conclusions: First, a vessel can only complete three NSR round trips compared with approximatively five round trips on the SCR, using an average value of 70 days per SCR trip (Drewry shipping Consultants 2018). The first trip starts in Shanghai on July 7, and the last trip on October 14. Second, due to the impact of ice thickness on sailing speed, the one-way transit time of each trip is always different. On the eastbound leg, the transit time is 31, 22, and 23 days, successively. On the westbound leg, 24, 22, and 29 days are required. Figure 2 shows that there are many instances when ice thickness induces a significant reduction in speed. During trip 2, it occurs after 8–10 days. Third, there is only one instance when icebreaker assistance is not required in any subzone, which is during trip 2.

Table 1 The 49 route subzones *Source* Cheaitou et al. (2019)

Zone	Location	Longitude	Latitude	Distance (nm)	Zone	Location	Longitude	Latitude	Distance (nm)
1	Hamburg Port	9° 58' 58"	53° 32' 24"	1566	26	*Zone 6. Sannikov Strait*	140° 0' 0"	73° 4' 26"	87
2	Elbe River entrance	9° 07' 37"	53° 53' 48"	108	27	Subzone 6.1	145° 0' 0"	73° 9' 58"	88
3	Zone 1. Murmansk Sea	34° 0' 0"	69° 26' 12"	125	28	Subzone 6.2	150° 0' 0"	73° 8' 14"	90
4	Subzone 1.1	39° 0' 0"	69° 55' 51"	101	29	Subzone 6.3	155° 0' 0"	72° 59' 9"	94
5	Subzone 1.2	45° 0' 0"	70° 19' 2"	100	30	*Zone 7. NSR*	160° 0' 0"	72° 42' 24"	106
6	Subzone 1.3	50° 0' 0"	70° 28' 49"	59	31	Subzone 7.2	170° 0' 0"	71° 43' 10"	115
7	Subzone 1.4	55° 0' 0"	70° 30' 16"	65	32	Subzone 7.3	175° 0' 0"	70° 58' 25"	104
8	Zone 2. Kara Gate	57° 0' 0"	70° 27' 18"	136	33	Wrangel Island	180° 0' 0"	70° 1' 12"	106
9	Subzone 2.1	60° 0' 0"	72° 20' 30"	115	34	Subzone 8.1	−175° 0' 0"	69° 49' 45"	67
10	Subzone 2.2	65° 0' 0"	74° 1' 20"	100	35	Subzone 8.2	−170° 0' 0"	69° 29' 24"	303
11	Subzone 2.3	70° 0' 0"	75° 27' 10"	71	36	*End of NSR*	−168° 58' 0"	69° 6' 0"	33
12	Subzone 2.4	75° 0' 0"	75° 56' 1"	17	37	Bering Strait	−169° 14' 60"	64° 5' 60"	139
13	Zone 3. NSR	79° 0' 0"	76° 42' 28"	80	38	Subzone 9.1	−170° 0' 0"	64° 4' 13"	156
14	Subzone 3.1	80° 0' 0"	77° 16' 29"	74	39	Subzone 9.2	−175° 0' 0"	63° 22' 51"	171
15	Subzone 3.2	85° 0' 0"	77° 36' 56"	69	40	Subzone 9.3	180° 0' 0"	62° 8' 8"	191
16	Subzone 3.3	90° 0' 0"	77° 53' 12"	66	41	Subzone 9.4	174° 59' 60"	60° 34' 52"	216
17	Subzone 3.4	95° 0' 0"	77° 33' 22"	64	42	Subzone 9.5	170° 0' 0"	58° 39' 11"	248
18	Subzone 3.5	100° 0' 0"	77° 48' 43"	65	43	Subzone 9.6	164° 59' 60"	56° 15' 59"	289
19	Zone 4. Vilkitsky Strait	105° 0' 0"	77° 58' 15"	68	44	Subzone 9.7	160° 0' 0"	53° 18' 27"	198
20	Subzone 4.1	110° 0' 0"	77° 42' 35"	73	45	Subzone 9.8	155° 0' 0"	49° 37' 45"	83
21	Subzone 4.2	115° 0' 0"	77° 20' 31"	79	46	Pacific	152° 0' 0"	47° 0' 0"	210
22	Subzone 4.3	120° 0' 0"	76° 51' 8"	88	47	Subzone 10.1	150° 0' 0"	46° 48' 20"	131
23	Zone 5. NSR	125° 0' 0"	76° 13' 7"	99	48	Subzone 10.2	145° 0' 0"	46° 9' 28"	862
24	Subzone 5.1	130° 0' 0"	75° 24' 37"	115	49	La Pérouse Strait	141° 56' 36"	45° 38' 41"	1164
25	Subzone 5.2	135° 0' 0"	74° 22' 60"	87				Total	8841

4.3 Service competitiveness

The previous section shows that, for NSR liner services, a fixed transit time and frequency of port calls cannot be offered. However, it could be assumed that punctual services could be put in place on a seasonal basis in the near future. For these services, the question regarding the competitiveness of such services compared with the two existing alternatives (the TRC and SCR) remains.

To answer this issue, the ice thickness–speed relationship as well as the speed–fuel consumption relationship are critical. Figure 3 presents these two curves, in line with assumptions provided in the model. As reported in Fig. 3, when ice thickness is more than 0.1 m, the vessel speed reduces, as this corresponds to the 1A ice-class vessel first threshold (Table 2). For an ice thickness equal to 0.5 m, the vessel cannot sail at more than 5 knots, and it becomes blocked when the thickness of the ice is greater than 0.9 m (Table 2). Assuming the same level of ice thickness along the NSR, the optimal speed is 15 knots or 70% of the design speed, which corresponds to a situation where the SFC is at its minimum level. When ice thickness is more than 0.3 m, the vessel has to slow down, and total fuel transit costs increase for two reasons. First, the speed in no longer close to 70–80% of design speed, and second, the impact from the transit time increase is higher than the effect of speed (fuel consumption) reduction.

Table 4 reports, for the three trips, the total costs. This includes the capital expenditure (CAPEX), operational expenditure (OPEX), and voyage costs (fuel and icebreaker fees), and the total cost per TEU. For all the trips, excluding the second trip eastbound, the use of an icebreaker is compulsory between one and seven zones, depending on the trip. Estimates are reported using two different fuel prices: the average 2009–2019 Rotterdam bunker price for HFO 380CST (3.5% sulfur content) and for MGO (0.1% sulfur content), plus 33% premium for Arctic conditions (Lasserre 2014).

Table 4 shows that, due to significant differences in the utilization rate of the vessel (Table 2), the cost per TEU is always higher on the eastbound trade than on the westbound trade. The share of fuel costs in total costs is obviously depending on the type of fuel used (HFO versus MGO), but also on the sailing conditions along the route. Fuel costs represent 72% (trip 1 with HFO) to 85% (trip 1 with MGO) of total costs on the westbound trip, and 55% (trip 1 with HFO) to 66% (trip 3 with MGO) on the eastbound trip.

Table 5 provides a synthesis of all westbound and eastbound results from Tables 1 and 3, as well as some indicative figures for the environmental and economic performance of the NSR, TRC, and SCR. Values for the TRC are from literature, while for the SCR, we used the average freight rates (quotations in USD per TEU), transit time, and CO_2 per TEU for Shanghai–Hamburg (and return) received by a major retailer company (more than 170,000 TEU/year) from six shipping lines in 2016 (3-year contract).

The main conclusions are that, in terms of cost, the NSR option can only represent a viable alternative on the westbound trip compared with the TRC or the SCR. This is still the case with high fuel prices (MGO) that could be implemented with more stringent Arctic regulations in the future. However, on the eastbound
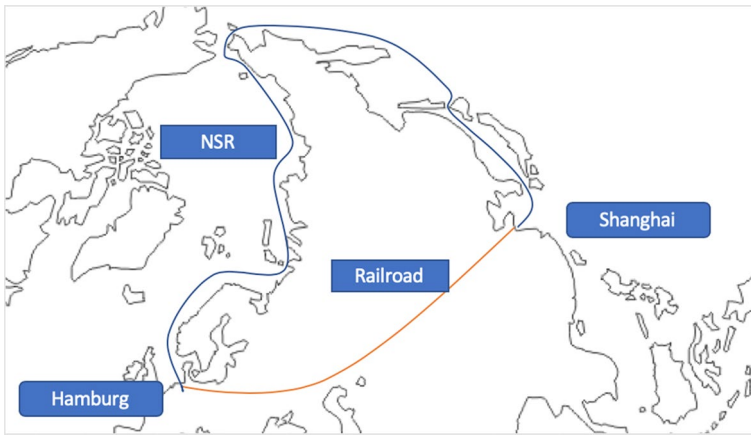
Fig. 1 Northern Sea Route—Silk Road. *Source* Authors

Table 2 Vessel (MV Maersk Venta) and main market characteristics

	1A ice-class
Daily $CAPEX_d$ (USD/day)[a]	7123
Daily $OPEX_d$ (USD/day)[b]	6121
SFC^M (g/kWh)[c] at 70% EL^M	170
PS^M (kW)[1]	19,620
F^A (ton/day)[d]	5.8
Design speed, S^{DS} (knot)[1]	19
Minimum speed, S^m (knot)[e]	3
Number of days at port, P (days)[f]	2
Loading capacity, K (TEU)[a]	3600
Bunker price C_b^M (USD/ton)—using HFO 380CST[a]	600
Bunker price C_b^M (USD/ton)—using HFO MGO[a]	970
Utilization rate westbound, α_1[g]	87%
Utilization rate eastbound, α_2[g]	60%
Ice threshold I_1^C (in m)[h]	0.1
Ice threshold I_2^C (in m)[h]	0.3
Ice threshold I_3^C (winter/spring and summer/autumn) (in m)[h]	0.7 and 0.9
$B = \left(\log \left(S^m \right) - \log \left(S^{DS} \right) \right) / \left(\log \left(I_3^C \right) - \log \left(I_1^C \right) \right)$	−0.8401
$A = S^{DS} \times \left(100 / I_1^C \right)^B$	0.0574

Source Authors based on [a]Clarksons Database (2018). For bunker price, average price of HFO 380CST (3.5% sulfur) and MGO (0.1% sulfur) in Rotterdam between 2009 and 2019, plus 33% premium due to Arctic, as in Lasserre (2014); [b]Hansa Opex Survey (2017) and Erikstad and Ehlers (2012); [c]Man B&W S70ME C8.5-TII (MAN Diesel Turbo 2018); [d]Melo and Echevarrieta (2014); [e]Kitagawa (2001); [f]Lasserre (2014); [g]Drewry Shipping Consultants (2018); [h]Faury and Cariou (2016)

Table 3 Trip details

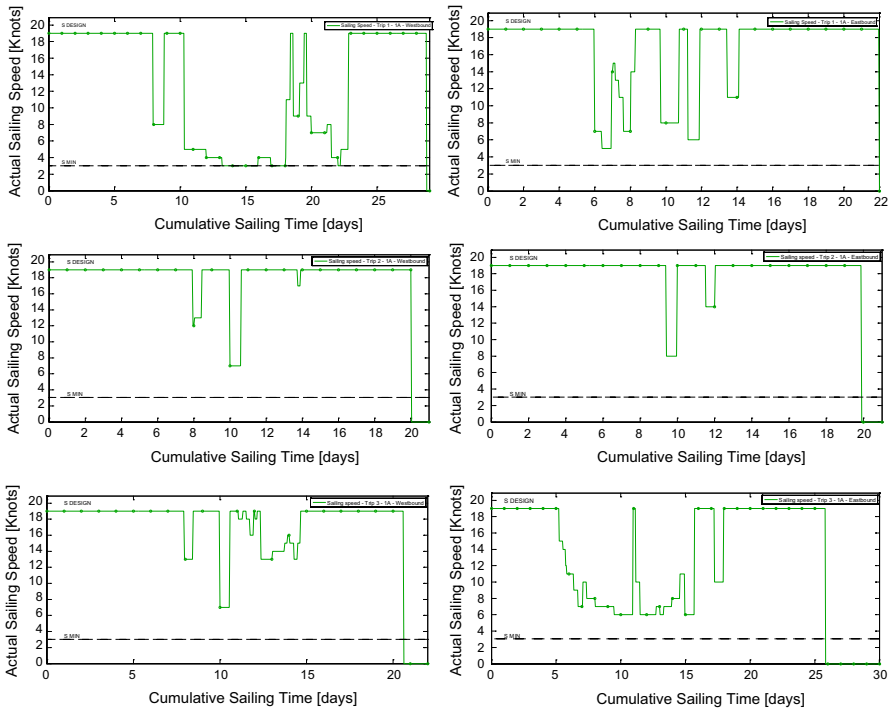| Voyage #	Departure Shanghai	Transit time westbound (days)	Arrival Hamburg	Transit time eastbound (days)	Arrival Shanghai	Total time (days)
1	07 Jul	30.7	07 Aug	23.9	31 Aug	54.6
2	31 Aug	21.9	22 Sep	21.9	14 Oct	43.8
3	14 Oct	22.6	05 Nov	27.8	02 Dec	50.7

Fig. 2 Sailing speed along the route during trip 1, 2, and 3

trip, the NSR is never competitive in comparison with the SCR. Furthermore, the NSR is never competitive in terms of CO_2 emissions compared with the SCR, and the TRC advantage is mostly related to shorter transit times. This confirms former studies that point out to the TRC competitiveness for high-value cargoes.

5 Conclusions

The paper uses three criteria (time, costs, and emissions) to compare the performance of the NSR, TRC, and SCR. From the analysis, sailing along the NSR brings some cost advantages during a limited period of time and for one leg only (westbound). For the other two parameters, either the rail connection (transit time) or the SCR shipping lane (CO_2 emissions) provide a better option. These conclusions are in line with existing literature and could be easily subject to further investigation, using different assumptions for the business case (other ice-class vessels, economic, technical, and environmental values). Moreover, this study provides specific conclusions that differ from existing literature.

First, it shows that, when considering ice conditions, deploying regular east/west services with a fixed NSR schedule and frequency is difficult to imagine. However, this does not apply to other shipping markets that do not require tight schedules (tramping, cruising), and this could be the subject of further investigation.
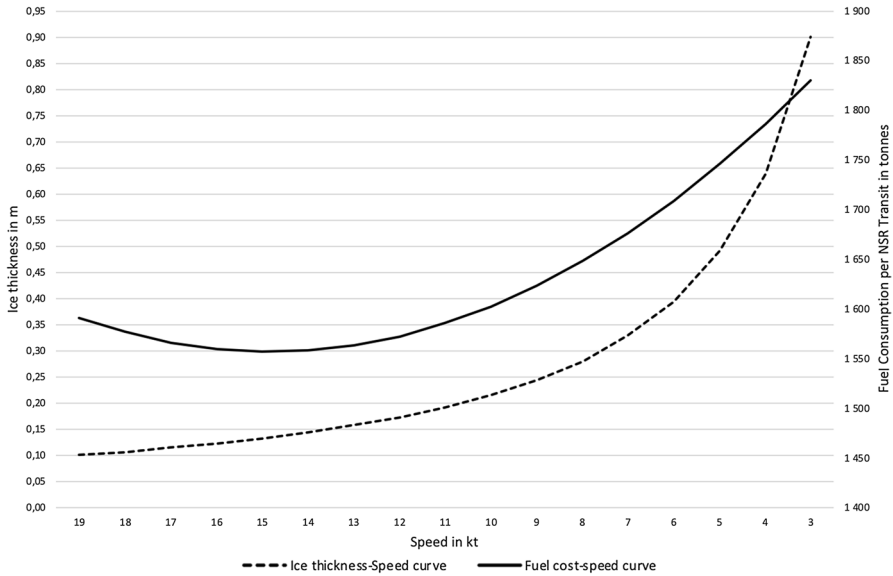
Fig. 3 Ice thickness–speed and fuel consumption–speed curves

Table 4 Economic results (in USD)

	Westbound costs				Eastbound costs			
	Bunker	Other	Total	Per TEU	Bunker	Other	Total	Per TEU
	HFO 380 cst bunker price 598.5 USD/ton							
Trip 1	1,070,309	751,231	1,821,540	581.59	1,036,677	584,623	1,621,300	750.60
Trip 2	1,028,438	482,008	1,510,446	482.26	1,026,942	289,487	1,316,429	609.46
Trip 3	1,028,820	490,228	1,519,048	485.01	1,053,194	745,708	1,798,902	832.83
	MGO bunker price 970.9 USD/ton							
Trip 1	1,736,279	751,231	2,487,510	794	1,681,720	584,623	2,266,343	1049
Trip 2	1,668,355	482,008	2,150,363	687	1,665,928	289,487	1,955,415	905
Trip 3	1,668,975	490,228	2,159,203	689	1,708,515	745,708	2,454,223	1136

Second, estimates demonstrate that the NSR is cost effective on the westbound voyage. However, even with high bunker prices, the lower utilization rates on the eastbound voyage mean that the NSR is not competitive. This is even the case during the summer period (trip 2), when the route is ice-free, and it relies on the assumption that the SCR and NSR utilization rates are similar. Future research could investigate how the NSR could be used as a complementary service for high-value commodities when sailing westbound and for empty containers when sailing eastbound. Under this configuration, shipping lines may charge higher prices on westbound voyages and lower on eastbound ones, as is done in the maritime SCR or TSR services.

Table 5 NSR, TRC, and SCR economic and environmental performance

	NSR westbound	NSR eastbound
	NSR—trip 1	
Cost [USD]/TEU [HF0; MGO]	[582; 794]	[750; 1049]
CO_2 [kg]/TEU	1609	2309
Transit time [days]	31	24
	NSR—trip 2	
Cost [USD]/TEU [HF0; MGO]	[482; 687]	[609; 905]
CO_2 [kg]/TEU	1590	2303
Transit time [days]	22	22
	NSR—trip 3	
Cost [USD]/TEU [HF0; MGO]	[485; 689]	[833; 1136]
CO_2 [kg]/TEU	1587	2321
Transit time [days]	23	28
	Trans-Siberian Railways connection	
Cost [USD]/TEU	2500[a]; 3000[b]; [1800–2200][c]	
CO_2 [kg]/TEU	4097[b]; [4500–5300][d]	
Transit time [days]	18[a]; 18[b]; 18–20[c]	
	Suez Canal Route (SCR)[e]	
Freight rate [USD]/TEU	797	546
CO_2 [kg]/TEU	660	630
Transit time [days]	30	36

Source Authors based on [a]Zhu et al. (2018); [b]Yang et al. (2018); [c]Verny and Grigentin (2009); [d]based on McKinnon and Piecyk (2010) using 18.8–22 g CO_2/ton-km, 12,000 km, and 20 ton/TEU. [e]Average value for Shanghai–Hamburg, ocean quotations from six shipping lines to a major retailer company (> 170,000 TEU per year procurement and with 10% margin reduction westbound and 5% eastbound)

Finally, the present work shows that, even with a limited ice thickness (trip 2, for instance), the NSR route and vessel characteristics mean that CO_2 emissions per TEU are higher than on the SCR, due to a gap between operating speed and design speed on some parts of the route. This environmental effect would be reinforced if considering that air emissions in Arctic areas (in particular black carbon) have higher negative environmental impacts (Lindstad et al. 2016; Zhu et al. 2018). However, using different vessel design and propulsion systems with alternative fuels may challenge these findings and should be subject to further research.

Appendix

The NSR fee per ice-class depends on the number of zones *n* (seven zones in total defined by the NSRA), the exchange rate (RUB/USD), the ship's gross tonnage and ice-class, and the season (winter/spring or summer/autumn). Information was retrieved from the FTS of Russia (2017), using an exchange rate of 0.0175 RUB/ USD. Next figure presents the seven NSR zones, and Table 1 is the estimated fee

The 7 NSR zone subject to Icebreaker Fee

Source: Authors based on http://d-maps.com/carte.php?num°car=3193&lang=fr

NSR fees [in USD] as a function of the number of zones with icebreaker assistance

Class	Season	ZONE 1	ZONE 2	ZONE 3	ZONE 4	ZONE 5	ZONE 6	ZONE 7
1A	Summer/Fall [USD]	191 127	229 345	267 572	305 799	344 026	382 245	382 245
	Winter/Spring [USD]	477 812	573 371	668 930	764 498	860 057	955 625	955 625

Source: Based on FTS of Russia (NSRA, 2018)

Fig. 4 Seven NSR zones subject to icebreaker fee. *Source* Authors based on http://d-maps.com/carte.php?num°car=3193&lang=fr

Table 6 NSR fees (in USD) as a function of the number of zones with icebreaker assistance. *Source* Based on FTS of Russia (NSRA 2018)

Class	Season	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6	Zone 7
1A	Summer/autumn [USD]	191,127	229,345	267,572	305,799	344,026	382,245	382,245
	Winter/spring [USD]	477,812	573,371	668,930	764,498	860,057	955,625	955,625

(IB) as a function of the number of zones when icebreaker assistance is needed (Fig. 4; Table 6).

References

Aksenov, Y., E.E. Popova, A. Yool, A.J.G. Nurser, T.D. Williams, L. Bertino, and J. Bergh. 2017. On the future navigability of Arctic sea routes: high-resolution projections of the Arctic Ocean and sea ice. *Marine Policy* 75: 300–317.

Benefyk, I.V., and S. Peeta. 2018. A binary probit model to analyze freight transportation decision-maker perspectives for container shipping on the Northern Sea Route. *Maritime Economics & Logistics* 20: 358–374.

Button, K., T. Kramberger, T. Vizinger, and M. Intihar. 2017. Economic implications for Adriatic seaport regions of further opening of the Northern Sea Route. *Maritime Economics & Logistics* 19: 52–67.

Cariou, P., and O. Faury. 2015. Relevance of the Northern Sea Route (NSR) for bulk shipping. *Transportation Research Part A: Policy and Practice* 78: 337–346.

Cheaitou, A., O. Faury, P. Cariou, S. Hamdan, and G. Fabbri. 2019. Ice thickness data in the northern sea route (NSR) for the period 2006–2016. *Data in Brief* 24: 103925.

Cheng, L.K. 2016. Three questions on China's "Belt and Road Initiative". *China Economic Review* 40: 309–313.

Cho, Y. 2012 The melting Arctic changing the world: New sea route. *International Convention Energy Security and Geopolitics in the Arctic: Challenges and Opportunities in the 21st Century*, January 9–10.

Clarksons Database. 2018. *Clarksons Database*. https://www.clarksons.net/portal. Accessed: 10 Jan 2018.

Comiso, J.C. 2012. Large decadal decline of the arctic multiyear ice cover. *Journal of Climate* 25 (4): 1176–1193.

Copernicus Database Ice Thickness. 2018. *E.U. Copernicus Marine Service Information database*. http://marine.copernicus.eu/. Accessed 10 Jan 2018.

Drewry shipping Consultant. 2018. *Drewry Container Forecaster*. https://www.drewry.co.uk/maritime-research-products/maritime-research-products/container-market-annual-review-and-forecast-20181 9. . Accessed 10 Jan 2018.

Erikstad, S.O., and S. Ehlers. 2012. Decision support framework for exploiting Northern Sea Route transport opportunities. *Ship Technology Research* 59 (2): 34–43.

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

Faury, O., and Givry, P. 2017. Evolution of ice class investment attractiveness depending on climatic and economic conditions. In *Proceedings of the IAME 2017 Conference*, Kyoto, Japan, June.

Fedi, L., O. Faury, and D. Gritsenko. 2018. The impact of the Polar Code on risk mitigation in Arctic waters: a "toolbox" for underwriters? *Maritime Policy and Management* 45 (5): 478–494.

Furuichi, M., and Otsuka, N. 2013. Effects of the Arctic Sea Routes (NSR and NWP) Navigability on Port Industry. *Arctic Knowledge Hub Report*.

Gritsenko, D., and T. Kiiski. 2016. A review of Russian ice-breaking tariff policy on the northern sea route 1991–2014. *Polar Record* 52 (2): 144–158.

Hansa International Maritime Journal. 2017. *Supplement OPEX Survey*.

IMO. 2014. *Third IMO greenhouse gas study*. London: International Maritime Organization.

Kitagawa, H. 2001. *The Northern Sea Route—The Shortest Sea Route linking East Asia and Europe*. Tokyo: Ship and Ocean Foundation.

Kiiski, T., T. Solakivi, and L. Ojala. 2016. Long-term dynamics of shipping and icebreaker capacity along the Northern Sea Route. *Maritime Economics & Logistics* 20: 375–399.

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: 144–161.

Lasserre, F., Huang, L., and Mottet E. 2018. *Conseil québécois d'études géopolitiques, L'essor des nouvelles liaisons ferroviaires Transasiatiques: Un décollage récent pour une idée ancienne*. https://cqegheiulaval.com/lessor-des-nouvelles-liaisons-ferroviaires-transasiatiques-un-decollage-recen t-pour-une-idee-ancienne/. Accessed 10 Jan 2018.

Lee, T., and H.J. Kim. 2015. Barriers of voyaging on the Northern Sea Route: a perspective from shipping Companies. *Marine Policy* 62: 264–270.

Lirn, T.-C., H.A. Thanopoulou, M.J. Beynon, and A.K.C. Beresford. 2004. An application of AHP on Transhipment port selection: a global perspective. *Maritime Economics & Logistics* 6 (1): 70–91.

Lindstad, H., R.M. Bright, and A.H. Strømman. 2016. Economic savings linked to future Arctic shipping trade are at odds with climate change mitigation. *Transport Policy* 45: 24–30.

Liu, M., and J. Kronbak. 2010. The potential economic viability of using the Northern Sea Route (NSR) as an alternative route between Asia and Europe. *Journal of Transport Geography* 18: 434–444.

Lloyd's list. 2018. *Maersk containership navigates Arctic Route, Lloyd's list*, 18 Sept 2018.

Man Diesel and Turbo. 2018. *Spec Man B. and W S70ME-C8.5-TII Project Guide Electronically Controlled Two-stroke Engines* (Copenhagen).

McKinnon, A., and Piecyk, M. 2010. *Measuring and managing CO_2 emissions of European Chemical Transport, Report for CEFIC*. https://cefic.org/app/uploads/2018/12/MeasuringAndManaging

CO2EmissionOfEuropeanTransport-McKinnon-24.01.2011-REPORT_TRANSPORT_AND_LOGISTICS.pdf.

Melia, N., K. Haines, and E. Hawkins. 2016. Sea ice decline and 21st century trans-Arctic shipping routes. *Geophysical Research Letters* 43: 9720–9728.

Melo, G., and Echevarrieta, I. 2014. *Resizing study of main and auxiliary engines of the container vessels and their contribution to the reduction of fuel consumption and GHG, International Association Maritime Universities Annual General Assembly*. IAMU AGA15. 441–452, LAUNCESTON.

Meng, Q., Y. Zhang, and M. Xu. 2017. Viability of transarctic shipping routes: A literature review from the navigational and commercial perspectives. *Maritime Policy and Management* 44 (1): 16–41.

Moon, D.S., D.J. Kim, and E.K. Lee. 2015. A study on competitiveness of sea transport by comparing international transport routes between Korea and EU. *Asian Journal of Shipping and Logistics* 31 (1): 1–20.

NSRA. 2018. *The Northern sea route administration*. http://www.nsra.ru/en/home.html. Accessed 10 Jan 2018.

Pelletier, S., and F. Lasserre. 2012. Arctic shipping: future polar express seaways? Shipowners' opinion. *Journal of Maritime Law and Commerce* 43 (4): 553–564.

Psaraftis, H.N., and C.A. Kontovas. 2010. Balancing the economic and environmental performance of maritime transportation. *Transportation Research Part D: Transport and Environment* 15: 458–462.

Solakivi, T., T. Kiiski, and L. Ojala. 2018. The impact of ice class on the economics of wet and dry bulk shipping in the Arctic waters. *Maritime Policy and Management* 45 (4): 530–542.

Solakivi, T., T. Kiiski, and L. Ojala. 2019. On the cost of ice: estimating the premium of Ice Class container vessels. *Maritime Economics & Logistics* 21: 207–222.

Song, D.-W., and K.-T. Yeo. 2004. A competitive analysis of Chinese container ports using the analytic hierarchy process. *Maritime Economics & Logistics* 6 (1): 34–52.

Stephenson, S.R., L.W. Brigham, and L.C. Smith. 2014. Marine accessibility along Russia's Northern Sea Route. *Polar Geography* 37 (2): 111–133.

Theocharis, D., S. Pettit, V.S. Rodrigues, and J. Haider. 2018. Arctic shipping: a systematic literature review of comparative studies. *Journal of Transport Geography* 69: 112–128.

Theocharis, D., S. Pettit, V.S. Rodrigues, and J. Haider. 2019. Feasibility of the Norther Sea Route: the role of distance, fuel prices, ice breaking fees and ship size for product tanker market. *Transportation Research* 129: 111–135.

Verny, J., and C. Grigentin. 2009. Container shipping on the Northern Sea Route. *International Journal of Production Economics* 122: 107–117.

Yang, D., L. Jiang, and A.K.Y. Ng. 2018. One belt one road, but several routes: a case study of new emerging trade corridors connecting the Far East to Europe. *Transportation Research Part A: Policy and Practice* 117: 190–204.

Yoo, B.Y. 2017. Economic assessment of liquefied natural gas (LNG) as a marine fuel for CO_2 carriers compared to marine gas oil (MGO). *Energy* 121: 772–780.

Yuan, C.-H., C.-H. Hsieh, and D.-T. Su. 2019. Effects of new shipping routes on the operational resilience of container lines: potential impacts of the Arctic Sea Route and the Kra Canal on the Europe-Far East seaborne trades. *Maritime Economics & Logistics*. https://doi.org/10.1057/s41278-019-00128-4.

Zhai, F. 2018. China's belt and road initiative: a preliminary quantitative assessment. *Journal of Asian Economics* 55: 84–92.

Zhang, Z., D. Huisingh, and M. Song. 2019. Exploitation of trans-Arctic maritime transportation. *Journal of Cleaner Production* 212: 960–973.

Zhu, S., X. Fu, A.K.Y. Ng, M. Luo, and Y.E. Ge. 2018. The environmental costs and economic implications of container shipping on the Northern Sea Route. *Maritime Policy and Management* 45 (4): 456–477.

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.