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Economic Feasibility of NSR/SCR-Combined Container Service on the Asia-Europe Lane: A New Approach Dynamically Considering Sea Ice Extent

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Abstract: The trend towards global warming and the rapid decline in the extent of summer Arctic sea ice over recent years has increased the feasibility of international Arctic shipping. In this study we propose a seasonal NSR (North Sea Route)/SCR (Suez Canal Route)-combined shipping service linking Shanghai and Rotterdam, using the Northern Sea Route during the economical navigable window but using the traditional Suez Canal Route at other times. Different from the previous literatures, this paper dynamically considers the sea ice extent in the model, which is more reasonable for the assessment of Arctic container shipping, because fuel consumption is highly related to ship speed, while ship speed is determined by the relative distances of ice-covered and ice-free route stages. A new approach is developed to predict the time points at which the ship enters and exits the ice-covered stage, given that both the ship position and the extent of sea ice are constantly changing. The results show that the NSR/SCR-combined Arctic container service can be more economical than the SCR, given lower NSR tariffs.

Keywords: Arctic container shipping, Northern Sea Route, Economic feasibility, Dynamic sea ice extent, Cost function

1. Introduction

Against the background of global warming, the Arctic Ocean is experiencing an unprecedented trend of declining sea ice, which makes the Arctic more navigable. The Arctic is a shortcut that can drastically decrease the distances among the three industrialized areas in northern hemisphere – North America, Europe, and East Asia. Wang *et al.* (2016) listed Arctic shipping lanes as important as the expanded Panama Canal. According to data from the NSIDC (National Snow and Ice Data Center) of the USA, from 1979 to 2015 the minimum sea ice extent (in September) of the Arctic declined on average 1.2% each year. From 2008, the sea route along the Russian Arctic coastline, known as the Northern Sea Route (henceforth NSR), was repeatedly ice free in September every year, which made Arctic shipping feasible. International transit shipping via the NSR began in 2009. In 2013, transited cargo via the NSR reached its peak at 135.6 million tons. The most important cargoes are petroleum (including LNG) from Northwest Russia and North Norway to East Asia, iron ore from Russia to China, and oil products from South Korea to North Europe. It can be found that the major cargoes via the NSR are liquid and bulk, and that general cargo is limited. One reason for this is that container shipping, which is characterized by punctuality, becomes subject to the wide variation of sea and ice conditions in the Arctic waters. However, in the long term, with the further diminishing of Arctic sea ice, container shipping may become economically viable using the NSR, because this route significantly shortens the distance of the sea route between East Asia and Northwest Europe, one of the most important trade corridors in the world, compared with the traditional Suez Canal Route (henceforth SCR).

In this study, an NSR/SCR-combined container service on the Asia-Europe lane is proposed. This service will use the SCR in the seasons when Arctic sea ice is too heavy for navigation, but will use the NSR in the 'economical navigable seasons'. There are many existing studies on economical comparison between the NSR and the SCR (see the reviews from Lasserre, 2014, and Meng et al., 2016). Many of them focus on non-container shipping, such as: Mineral fertilizer shipping (Schøyen and Bråthen, 2011; Cariou and Faury, 2015); iron ore shipping (Otsuka et al., 2013); LNG shipping (Raza and Schøyens, 2014; Otsuka et al., 2013); frozen fish shipping (Otsuka et al., 2013); and oil tanker shipping (Faury and Cariou, 2016). In particular, Pruyn (2016) innovatively introduced a 'consistent maritime macro- to micro-economic model' to generate the annual and weekly trade flows between 16 areas in the world, including 4 areas involved in Arctic shipping. Although these studies enrich the Arctic shipping literature, they are not applicable to Arctic container shipping due to the differing nature of tramp and liner shipping.

There are also studies on Arctic container shipping, such as Arpiainen et al. (2006), Verny and Grigentin (2009), Liu and Kronbak (2010), Xu et al. (2011), Omre (2012), Furuichi and Otsuka (2014), Lasserre (2014), Wang et al. (2016), Zhang et al. (2016), and Zhao et al. (2016). As container liner shipping must be continuously active throughout the year, during the non-navigable season of the NSR container liners have to sail the traditional route—the SCR. Most of these papers consider given navigable windows for NSR shipping. Among them, Xu et al. (2011) proposed one month (i.e. September) of using the navigable window on the NSR, for an NSR/SCR-combined service with multi-port calling; Omre (2012) studied a combined service between Rotterdam and Yokohama, and assumed 14 'ice alternatives' with different combinations of ice conditions over 10 NSR sections; Furuichi and Otsuka (2014) assumed 5 different scenarios of navigable window (lasting 105, 135, 165, 195, and 225 days respectively); Zhao et al. (2016) applied a two-stage optimization model containing the mode for shipping network design with multi-port calling, and considered 3 levels of navigable window (4, 6, and 8 months). It should also be noted that Omre (2012) is the only study so far which assesses the economic feasibility of Arctic shipping when taking into account the impact of ice resistance on the fuel consumption function. In these works, the economic feasibility varies in terms of different pairs of origins and destinations: Omre (2012) and Furuichi and Otsuka (2014) considered Yokohama as the only destination in East Asia, and they concluded that the NSR/SCR-combined route is economical under certain sea ice conditions or bunker prices; while Zhao et al. (2016) considered Chinese ports as destinations, and concluded that the NSR/SCR-combined route is not economical unless the NSR navigable window is 8 months long and that during this time the NSR ice-breaking fee is zero. Although Xu et al. (2011) included Chinese ports as destinations and concluded that the NSR/SCR-combined route is economical, that work did not consider the additional cost of ice-class ships.

Besides these economic assessments of NSR container shipping, it is noted that a few studies have focused on the path optimization problem by applying real or projected ice condition data to the NSR. These studies include Smith and Stephenson (2013), Nam et al. (2013), and Choi et al. (2015). A few qualitative works applied survey methods to analyze the preferences of shipping companies as to Arctic shipping, for example, Lasserre and Pelletier (2011), Lee and Kim (2015), and Beveridge et al. (2016). These studies pointed out that most shipping companies hold a negative attitude toward NSR container shipping. Is this attitude reasonable for a container liner company? This paper will re-examine the question from a new perspective, using real data.

This study will build upon the previous literatures by taking into consideration the impact of ice resistance on the fuel consumption rate, following Omre (2012). Moreover, this study will enrich the previous literatures by introducing a new approach that dynamically considers the extent of sea ice affecting NSR container shipping, instead of a static navigable window. By applying this approach, a ship can recognize its 'economical navigable window', a dynamic window during which certain light ice conditions may also be considered as navigable if it can make the NSR transit more economical. This dynamic consideration of sea ice extent is more reasonable for the assessment of Arctic container shipping, because fuel consumption is highly related to ship speed, while ship speed is determined by the relative distances of ice-covered and ice-free stages.

The paper is organized as follows: In section 2 we introduce the new approach we developed to solve our proposed problem. In section 3 we build our assessment model based on a shipping cost function. In section 4 an empirical study is conducted by applying real data to compare the costs of the NSR/SCR-combined Arctic service and the traditional SCR service. In the final section the conclusion of this study is drawn.

2. Methodology

2.1 Spatiotemporal Mapping

To account for the relative changes between the ship position and the extent of Arctic sea ice that makes the distances of ice-covered and ice-free stages ever-changing, we develop a new approach—which we have named Spatiotemporal Mapping. This method relies on Cartesian coordinates, in which the x-coordinate represents the time, while the y-coordinate indicates the distance from a certain port in Northwest Europe via the NSR. In this study we choose Rotterdam in Northwest Europe and Shanghai in East Asia as being the only two port calls. Using Google Earth, the distance between Rotterdam and Shanghai via the NSR is measured as 7,630 nautical miles (going through the north of the New Siberian Islands and the Novaya Zemlya), while the traditional route is 10,472 nautical miles, of which 87 nautical miles are within the Suez Canal. Figure 1 shows the Arctic section of the route applied in this study. On the y-coordinates, we assume that Rotterdam is located at y=0 and Shanghai is located at y=7603.

Please insert Figure 1 here

Figure 1. Arctic Section of the Proposed NSR/SCR-Combined Route

Based on the mid-month Arctic sea ice extent of each month in 2015 from the database of the National Snow and Ice Data Center (NSIDC), the seasonal changes of the Arctic sea ice extent are mapped as in Figure 2. In this figure, the boundary of Arctic sea ice with its seasonal variation is shown in bold broken lines. The change in sea ice extent between every two dates is assumed to be linear. The tracks of each voyage of a sample container liner via the NSR can also be seen mapped in Figure 2. The tracks of the sample ship (assuming a weekly service, with 12 ships deployed that stay one day at each port of call) are shown by the thin broken lines. The slope of the broken line reflects the ship's speeds: a steeper slope means a faster speed and *vice versa*. Noting the speed difference between that in the ice-covered stage and in ice-free stage, the shift of speeds clearly occurs when the ship steams in and out of the ice field (e.g. points A and B in Figure 2). The speed in the ice-covered stage (denoted by *VI* henceforth) is assumed be equal to the speed of the escorting Atomflot (Russian nuclear icebreaker fleet that mainly services the NSR) icebreakers, which is in practice mostly set at 3-5 knots. Here the level ice thickness is assumed to be 1 meter, and the speed of most diesel-engine icebreakers in 1-meter level ice is lower than 3 knots. In contrast, the nuclear icebreakers are much more powerful than diesel-engine icebreakers, in this study we suggest three scenarios of *VI*: 3, 4, and 5 knots. Although some studies, for example Liu and Kronbak (2010), assumed that the average speed along the NSR in spring is above 6 knots, we adopted a more conservative *VI* (3-5 knots) for the sake of higher safety in ice navigation along our proposed route, which goes north of the New Siberian Islands where more occasional heavy ice conditions may be confronted. The speed required in the ice-free stage is affected by both the distance of the ice-covered stage and the speed in it. Each single round trip of the voyage is divided into an eastbound part (from Rotterdam to Shanghai) and a westbound part (from Shanghai to Rotterdam).

Please insert Figure 2 here

Figure 2. Spatiotemporal Mapping of NSR Sea Ice Extent and Tracks of a Ship for a Year-round Service

Since, for liner shipping, the transit time of each voyage is fixed, the longer the ice-covered stage is that a ship goes through, the higher the speed that the ship needs to sail in the ice-free stage, and vice versa. By adopting the Spatiotemporal Mapping approach, we calculate the required speeds in the ice-free stage of different voyages under different combinations of *VI* and the number of ships deployed *N* in a year by using the software Mathematica 5.0. The corresponding times spent in ice-free and ice-covered stages of different voyages can also be obtained. Figure 3 shows four cases in which *N* is set at 6 and 12 ships respectively, and the speed in the ice-covered stage *VI* is assumed to be 3 and 5 knots respectively. Generally speaking, the maximum speed of a container liner is 25 knots, which is reflected in Figure 3. Under this limitation, on most days in a year it is infeasible to sustain an NSR liner service with 6 ships, because the required speed in ice-free stage is higher than the 25 knots needed to maintain the schedule, which is technologically infeasible. On the other hand, a service with 12 ships (*N*=12) is technically feasible. However, though feasible, it does not mean that the NSR/SCR-combined service is more economical than the pure SCR, because the faster speed may incur a higher cost for the service. The results of the speeds we obtained in ice-free stage and the times spent in both ice-free and ice-covered stage on the different voyages will be used in the containership cost model we build in the next section.

Please insert Figure 3 here

Figure 3: Eastbound Speed in Ice-Free Stage (left) and Time Spent in Ice-Covered Stage (right) According to Departure Date from Rotterdam under Different Conditions

In this study, the sea ice extent of 2015 is used, because it varies not widely in recent years. Figure 4 shows the monthly average Arctic sea ice extent from 2000 to 2016. In the long-run, however, the decline of sea ice extent should be discussed.

Please insert Figure 4 here

Figure 4: Monthly average Arctic sea ice extent from 2000 to 2016

Source: National Snow and Ice Data Center. ftp://sidads.colorado.edu/DATASETS/NOAA/G02135/

2.2 Shipping cost model

In this section we build a cost function to calculate the annual costs per TEU of the NSR/SCR-combined Arctic container service and the SCR container service, respectively.

The shipping cost can be divided into the capital cost, the operating cost, and the fuel cost, as well as the canal tolls and icebreaker fees. The capital cost is the value depreciation of ships. The operating cost includes repair and maintenance fees, insurance fees, administration costs, crew wages, and other miscellaneous costs. The fuel cost is related to the bunker price, the duration of the voyage, and the fuel consumption rate, which is proportional to the power output of the main engine. For a ship operated in open water, the power output is proportional to the cubic of the speed of the ship, according to the 'propeller law'. In addition, for a ship operating in an ice field, additional power is required to overcome the ice resistance. The fuel cost of an Arctic voyage is:

$$CFVA_k = PF(TI_k \cdot FI_k + T_k \cdot F_k) \qquad (1)$$

where $CFVA_k$ is the fuel cost of the Arctic voyage k (US$); PF is the bunker price (US$/ton); TI_k is the time spent in the ice-covered stage of the voyage k (day); FI_k is the fuel consumption rate in the ice-covered stage of the voyage k (ton/day); T_k is the time spent in the ice-free stage of the voyage k (day); F_k is the fuel consumption rate in ice-free stage of the voyage k (ton/day). Considering the propeller law and the ice resistance, FI_k and F_k are:

$$FI_k = FMAX\left(a_1 \frac{VI^3}{VMAX^3} + \frac{P_s}{BHPMAX}\right)$$

$$F_k = FMAX \cdot a_1 \frac{V_k^3}{VMAX^3}$$

where *FMAX* is the maximum fuel consumption rate of a ship sailing at its maximum speed; a_1 is the additional fuel consumption coefficient induced by ice-class ships in sailing; *VI* is the speed in the ice-covered stage; P_s is the additional power required to overcome the ice resistance; *BHPMAX* is the maximum power output of the main engine; V_k is the speed in ice-free stage of the voyage *k*. So Equation (1) can be further expressed as:

$$CFVA_k = PF \cdot FMAX\left(TI_k\left(a_1 \frac{VI^3}{VMAX^3} + \frac{P_s}{BHPMAX}\right) + T_k a_1 \frac{V_k^3}{VMAX^3}\right) \tag{2}$$

To calculate the additional power required to overcome the ice resistance, we apply the equations of Finnish-Swedish ice-class rules (Juva and Riska, 2002), which have been widely applied in ice-class ship design. Under Finnish-Swedish ice-class rules, the additional power P_s needed to overcome the channel ice resistance is calculated as:

$$P_s = K_p \frac{R_{ch}^{3/2}}{D_p} \tag{3}$$

where R_{ch} is the rule channel resistance (*kN*); D_p is the propeller diameter (m); K_p is a coefficient differing with the number of propellers and propeller type or machinery. For controllable pitch propellers or electric or hydraulic propulsion machinery, K_p=2.03 for 1 propeller, 1.44 for 2 propellers, and 1.18 for 3 propellers; for fixed pitch propellers, K_p=2.26 for 1 propeller, 1.6 for 2 propellers, and 1.31 for 3 propellers. According to Finnish-Swedish ice-class rules, R_{ch} is calculated as:

$$R_{ch} = C_1 + C_2 + C_3(H_F + H_M)^2(B + 0.658H_F) + C_4 L H_F^2 + C_5 X \frac{B}{4} \tag{4}$$

$$X = \begin{cases} 5, & \text{if } \left(\frac{L \cdot DR}{B^2}\right)^3 < 5 \\ \left(\frac{L \cdot DR}{B^2}\right)^3, & \text{if } 5 \leq \left(\frac{L \cdot DR}{B^2}\right)^3 < 20 \\ 20, & \text{if } \left(\frac{L \cdot DR}{B^2}\right)^3 \geq 20 \end{cases}$$

where H_F is the thickness of the brash ice layer which is displaced by the bow and is moved to the side against the parallel midbody (m); H_M is the thickness of the brash ice in the middle of the channel (m); B is the breadth of the ship (m); L is the length between perpendiculars of the ship (m); DR is the draft of the ship (m). H_F is approximate to $0.26+(BH_M)^{0.5}$. C_3=459.993, C_4=18.783, C_5=825.6. For a ship with a bulbous bow, C_1 and C_2 are:

$$C_1 = f_1 \frac{B \cdot L}{2DR/B + 1} + 2.89(f_2 B + f_3 L + f_4 B \cdot L)$$

$$C_2 = 6.67(g_1 + g_2 B) + g_3 \left(1 + 1.2\frac{DR}{B}\right)\frac{B^2}{\sqrt{L}}$$

where f_1=10.35, f_2=45.8, f_3=2.94, f_4=5.8, g_1=1537.3, g_2=172.3, and g_3=398.7 (Juva and Riska, 2002). Substituting the above variables into Equation (3) and inputting Ps to Equation (2), we obtain the Arctic voyage fuel cost $CFVA_k$.

On the other hand, the fuel cost of an SCR voyage is:

$$CFVT = PF(T \cdot F + T_S \cdot F_S) \tag{5}$$

where $CFVT$ is the fuel cost of an Asia-Europe voyage via the Suez Canal (because the speed of every voyage is identical, thus the subscript of each voyage is omitted in the following equations). In the Suez Canal, the sailing speed i is limited by regulations, therefore the fuel consumption rates outside and in the canal are different. T is the time spent in the stages outside the Suez Canal of one voyage; F is the fuel consumption rate in the stages outside the Suez Canal; T_S is the time spent in the Suez Canal; F_S is the fuel consumption rate in the Suez Canal.

In Equation (5), F and F_S are calculated as:

$$F = FMAX \cdot a_1 \frac{V^3}{VMAX^3} = FMAX \cdot a_1 \frac{L^3}{VMAX^3 (24T)^3}$$

$$F_S = FMAX \cdot a_1 \frac{V_S^3}{VMAX^3} = FMAX \cdot a_1 \frac{L_S^3}{VMAX^3 (24T_S)^3}$$

where V is the average speed outside the Suez Canal; L is the distance between the Asian port and the European port outside the Suez Canal; V_S is the average speed in the Suez Canal; L_S is the distance of the Suez Canal. In this study, V_S is set to be 8 knots, which is approximate to the upper speed limit of the Suez Canal (according to Suez Canal Authority, the upper speed limit is 8.64 knots). Notice V and V_S are in knots but T and T_S are in days, so T and T_S should be multiplied by 24 when they are converted to hours. Substitute F and F_S into Equation (5) and we obtain:

$$CFVT = PF \cdot a_1 \frac{FMAX}{VMAX^3} \left(\frac{L^3}{24^3 T^2} + \frac{L_S V_S^2}{24} \right) \tag{6}$$

The time spent in the sea legs outside the Suez Canal T is the total time minus the time spent at port and the time spent in the Suez Canal. To maintain a weekly service, the number of ships should be equal to one seventh of the total transit days. So Equation (6) can be rewritten as:

$$CFVT = PF \cdot a_1 \frac{FMAX}{VMAX^3} \left(\frac{L^3}{24^3 \left(\frac{7N}{2} - T_P - \frac{L_S}{24 V_S} \right)^2} + \frac{L_S V_S^2}{24} \right) \tag{7}$$

where N is the number of ships deployed in the service; T_P is the time spent at port (in days). From the perspective of the carrier, for a certain voyage k, the cheaper of the

NSR/SCR and SCR routes will always be chosen. Thus, we define CFV_k as the optimal fuel cost of voyage *k*:

$$CFV_k = \min\{CFVA_k, CFVT\} \tag{8}$$

The capital cost is determined by the number and new-building prices of ships deployed. We assume that the lifetime of each ship is 10 years, as Otsuka *et al*. (2013) suggested. Then, based on straight-line depreciation, the annual value depreciated is set as 1/10 of the new-building price. The annual capital cost of one ship, represented by *CCY*, is:

$$CCY = a_2 \frac{CS}{10}$$

where *CS* is the new-building price of a ship; a_2 is the additional price coefficient for ice-class ships. To maintain a weekly service, the number of round trips a ship can complete in a year is about $365/(T+T_S)$ or $365/(7N)$, so the capital cost of a round trip (containing one eastbound voyage and one westbound voyage), represented by *CCR*, is:

$$CCR = \frac{CCY}{\frac{365}{7N}} \approx a_2 N \frac{CS}{52 \times 10}$$

The actual stated operating cost varies widely between different literatures. Zhao *et al.* (2016) suggested that it is around 80% of the capital cost for a 4800TEU container ship. Zhang *et al*. (2016) thought that this ratio is 56% for a 5100TEU ship. Tran and Haasis (2015) indicated that this ratio varies from 16% (for an 11000TEU ship) to 52% (for 1200TEU). In this study, we assume the operating cost of a ship, represented by *COR*, to be 50% of the capital cost, this being the average value of the above sources:

$$COR = \frac{1}{2} CCR$$

Notice that the operating cost includes insurance fee. The insurance fee of NSR is very different from it of the SCR. For the NSR, the potential damages from bad ice or weather conditions, for example ice collision, will affect the insurance fee heavily; whereas for the SCR, the piracy attacks around Somalia and Malacca are serious concerns. Because of the limited data accessibility, in this paper we do not consider the difference of insurance cost.

The total shipping cost of a round trip for the NSR/SCR-combined container service is:

$$CR_{ij} = CCR + COR + CFV_i + CFV_j + FEE \tag{9}$$

where CR_{ij} is the total shipping cost of a round trip, which consists of the eastbound voyage i and the westbound voyage j, and they must be two sequential voyages in order to keep the schedule consistent; FEE is the NSR tariffs. Although the Russian authorities issue the maximum level of NSR tariffs, in practice the actual NSR tariffs are settled by negotiation between shipowners and Atomflot (Otsuka *et al*., 2013; Moe, 2014). In this study, we provide 6 levels of the NSR tariffs using Suez Canal tolls as a benchmark. We assume the ratios of the NSR tariffs to the Suez Canal tolls are 1, 0.8, 0.6, 0.4, 0.2, or 0. When the ratio is 1, these two fees are equal; whereas it is 0, the NSR is free of tariff.

For comparison, the shipping cost of a pure SCR Asia-Europe container service is calculated as:

$$CR = CCR + COR + 2CFVT + TOLL \tag{10}$$

where $TOLL$ represents the Suez Canal tolls. The Suez Canal tolls are based on the rates issued by the Suez Canal Authority and the Suez Canal net tonnage. In this study, the Suez Canal net tonnage is replaced by the gross tonnage, because the former is difficult to obtain, and the two tonnages are similar in value. Let $a_3 = FEE/TOLL$. Based on the aforementioned assumption, a_3 is given by 1, 0.8, 0.6, 0.4, 0.2, and 0.

In Equation (10), $2CFVT$ represents the sum of voyage fuel costs of one eastbound and one westbound voyage in a round trip. a_1 (additional fuel consumption coefficient for the ice-class ships) and a_2 (additional price coefficient for the ice-class ships) are both set as 1, because in this case only the SCR is used, and non-ice-class ships are deployed.

With these equations, the average costs per TEU shipped in a round trip by the NSR/SCR-combined service and the SCR service can be calculated and compared. The average cost per TEU shipped in a round-trip of the NSR/SCR-combined Arctic service, represented by *ACS*, is calculated by dividing the sum of the costs of all the round trips made in a year by the total TEU shipped in a year:

$$ACS = \frac{\min\left\{\sum_{n=1}^{52} CR_{d+7n,d+7n+7N/2+T_P} | d=1,2,3,4,5,6\right\}}{52Q} \quad (11)$$

where Q is the total TEU shipped per round trip (bilateral between Northwest Europe and East Asia). The subscripts of *CR*, denoting the voyage codes, are here represented by the departure dates in a year. The intervals between two voyages are 7 days. The average cost per TEU shipped in a round trip of the SCR service, represented by *ACT*, is calculated as:

$$ACT = \frac{CR}{Q} \quad (12)$$

By changing variable N to minimize *ACS* and *ACT*, the difference between them can be obtained:

$$\Delta C = \min\{ACS(N) | N \in \mathbb{N}\} - \min\{ACT(N) | N \in \mathbb{N}\} \quad (13)$$

Notice that the number of ships deployed N is a natural number. The range of N is constrained by the upper limit of the ship speed. In this paper, we consider that the shipping schedules for both NSR shipping and SCR shipping under the proposed period are same, which leads to identical trade volumes, freight rates, and transit times. For simplicity, the time value is not taken into account into the paper.

3. Empirical study

In this section, we apply our model to different scenarios with real data. At the beginning, the following assumptions are made:

1) Ice-class 1A (Finnish-Swedish) or ARC4 (Russian) ships are used in our estimation. They are two of the most widely used ice-classes, and roughly equivalent. Both of them are allowed to sail the whole NSR, with an icebreaker escort under light or medium ice conditions in summertime (from July to November). The additional fuel consumption coefficient a_1 and the additional price coefficient a_2 for the NSR/SCR-combined Arctic container service are both set to be 1.1, based on the results regressed with ship data from Clarkson database (see Figure 5). Erikstad and Ehlers (2012) also provided a parameter in their paper of 1.095, which is close to our estimated result.

2) Only Shanghai in East Asia and Rotterdam in Northwest Europe are called at in the service. Although this assumption violates the reality that most container services are multi-port calling but not point-to-point, most previous Arctic container shipping studies assumed a point-to-point service (e.g. Verny and Grigentin, 2009; Liu and Kronbak, 2010; More, 2012; Furuichi and Otsuka, 2014), which replaces port ranges with two end ports. This simplification will prevent the results from over-complication without losing generality.

3) The thickness of level sea ice and brash ice is assumed to be 1 meter, which is normal in summertime under the current trend of Arctic sea ice retreat (Aksenov, *et al*., 2017).

4) Container ships are assumed to be fully loaded on westbound voyages (from East Asia to Northwest Europe), and half loaded on eastbound voyages (from Northwest Europe to East Asia). This is roughly based on the bilateral container traffic ratio of the Asia-Europe lane listed in the Clarkson database.

Please insert Figure 5 here

Figure 5. Ratios of ARC4 to Normal Ships in Fuel Consumption Rate and New-building Price Source: Clarkson database

Considering the uncertainty of variables in our model, we propose several scenarios to test as follows:

1) The speed of icebreakers in the ice-covered stage is set as 3, 4, and 5 knots, as mentioned in Section 2.

2) According to market price fluctuation in the real world, the bunker price is set to range from 100 to 700 US$/ton, with intervals of 100 US$/ton each.

3) Five ship types with different carrying capacities are considered: 8000 TEU, 10000 TEU, 12000 TEU, 14000 TEU and 16000 TEU. These types are represented by five typical ships, and their parameters (see Table 1) are inputted to the model. Notice that most Arctic studies assumed that the container ship is no bigger than 4000 TEU, taking into account the limitation of shallow water in the Sannikov Strait (13m deep) and the beam of existing nuclear icebreakers (30m wide). However, in this paper, the NSR route

is assumed to be north of the New Siberian Islands, that is to say, the Sannikov Strait is bypassed and the depth of Sannikov Strait is not a limitation.

4) Six NSR tariffs levels are considered. We use a_3 to represent the ratio of the NSR tariffs to the Suez Canal tolls. It is assumed to be 1, 0.8, 0.6, 0.4, 0.2, or 0.

Table 1. Parameters of Applied Typical Ships

Please insert Table 1 here

Under these assumptions, we apply the model built in Section 3 to calculate the average costs per TEU of the two routes under different scenarios. The results are partly presented in Table 2. Because the empirical study contains 3 icebreaker speed levels, 5 ship types, 7 bunker price levels, and 6 NSR tariff levels. The complete results are too bulky to be fully shown by tables. In Table 2, we only show the results under the combinations of two levels of VI - 3 and 5 knots, and two levels of a_3 - 0 and 1.

Table 2. Results from Cost Model

Please insert Table 2 here

From Table 2, we find that the NSR/SCR-combined service is always more expensive than the SCR service when the NSR tariffs equal to the Suez Canal tolls (i.e. a_3=1), whereas it is more economical under most scenarios when the NSR tariffs are free (i.e. a_3=0). The cost per TEU of the NSR/SCR-combined service ranges from \$188.0 to \$389.3 on different scenarios; while that of the SCR service ranges from \$195.4 to \$371.7. The cost (cost/TEU) difference between the NSR/SCR-combined service and the SCR service varies between -11.7% and 4.9%.

These relative cost differences in Table 2 are shown in Figure 6.

Please insert Figure 6 here

Figure 6. Relative Cost Differences between NSR/SCR-combined and SCR Services by Bunker Prices and Ship Types

Among these scenarios, we find that under the condition of a_3=1 as two top sub-figures of Figure 6 shows, when the bunker price is 300-500$/t, the cost disadvantage of the NSR/SCR-combined service is the smallest. Its cost disadvantage becomes larger with the decrease or increase of the bunker price. This is because, a low bunker price will reduce the competitiveness of NSR because the fuel cost saving becomes minor; while a higher bunker price will lead the slow steaming strategy adopted by the carriers, then they need deploy more ships which increase the capital cost. The higher capital of ice-class ships will offset the fuel cost saving.

However, when a_3=0, as two bottom sub-figures of Figure 6 show, the NSR/SCR-combined service becomes more economical than the SCR under most scenarios. The advantage of the combined service reaches its top when the bunker price is 200-300$/t given VI=5, or 100-200$/t given VI=3. This indicates that when the NSR tariffs sufficiently decrease, the optimal range of bunker price for the NSR/SCR-combined service becomes lower.

From Table 2, we can see there will be 21 to 104 voyages using the NSR in a yearly service, depending on different scenarios. Notice that 104 voyages means NSR route is used all the year, which is enabled under the condition that NSR tariffs are free and the icebreaker speed is sufficiently high. Basically, for all scenarios, a higher bunker price will lead to more voyages using the NSR. This implies that a higher bunker price will increase the percentage of NSR voyages in the total voyages on the combined service.

We also find that, on both routes, the larger the deployed ships are, the lower the average cost is, regardless of other conditions. This reflects the economies of scale in ship size on the NSR, and it also means that if a commercial shipping service adopts the NSR in the future, extra-large container ships will be preferred. This will challenge existing technologies for ice-class ships and icebreakers. The biggest ship that has sailed the NSR up to now, the Suezmax tanker *Vladmir Tikhonov*, has a 280.5m length overall, a 50m beam, and a 16.28m draft, which is smaller in size than the largest model container ship used in this study (*CMA CGM Marco Polo*). Most ships that have sailed the NSR are far smaller than this ship.

Figure 7 shows the overall cost comparison of these two routes under various scenarios.

Please insert Figure 7 here

Figure 7. Cost Advantage of NSR/SCR-combined Route over SCR under Different Condition Combinations

Each sub-figures of Figure 7 indicates a ship type. The columns denote the bunker price levels, and the rows represent the NSR tariff levels. In the cells with horizontal stripes, the NSR/SCR-combined service is more economical than the SCR given *VI*=5. In the grid cells, the NSR/SCR-combined service is more economical given *VI*=4 or *VI*=5. The black cells denotes that the NSR/SCR-combined route is always more economical while the blank cells indicates that the SCR is always more economical. From this figure, we can also find that the combined service is less economical for the ships of 14000 TEU and 16000 TEU, when the NSR tariffs are larger than 0.4 times of the Suez Canal tolls. For the ship of 10000 TEU and 12000 TEU, the combined service is always more economical if the NSR tariffs are zero.

4. Conclusion

In this study we proposed a new approach to investigating the economic feasibility of the NSR/SCR-combined Arctic container service with an ice-class ship (1A or ARC4) on the Asia-Europe lane, using the SCR service with normal ships as a benchmark. This approach considers the constant changes in ship position and extent of sea ice, which provides a dynamic navigable time window instead of a static navigable time window broadly applied in the previous literatures.

Based upon this approach, a cost model was built and applied, using real data to compare the average costs of the NSR/SCR-combined Arctic container service and the SCR service. Several scenarios considering different levels of icebreaker speed, bunker price, ship size, and NSR tariffs were proposed, and we reach the following findings:

1) The NSR/SCR-combined Arctic service is less economical than the SCR service when the NSR tariffs are as 0.8 times as the Suez Canal tolls or more than 0.8 times, regardless of other conditions. Nevertheless, if the NSR tariffs decrease sufficiently, the combined service becomes more competitive. For example, when the icebreaker speed is 3 knots and the NSR tariffs are zero, the average cost per TEU of the NSR/SCR-combined Arctic service is 2.0% lower than the SCR.

2) The change of bunker price leads to a two-sided effect. On one hand, a higher bunker price will benefit the use of the NSR because of fuel cost saving. On the other hand, when bunker price is sufficiently high, carriers tend to lower ship speed and deploy more ships, and as a result the higher capital of ice-class ships required by the NSR will offset the fuel cost saving. This trade-off makes the medium level of bunker price (such as 200-500$/t) the most favorable condition to the NSR/SCR-combined service. However, we notice it is also subject to the change of other factors. For instance, when the icebreaker speed is 3 knots and the NSR tariffs are zero, the effect of the fuel cost saving becomes minor compared to the capital cost of ice-class ships. Under such condition, a lower bunker price (such as 100-200$/t) becomes the optimal condition.

3) There will be 21 to 104 voyages passing through the NSR under different scenarios for the NSR/SCR-combined service. A higher bunker price tends to enable more voyages passing through the NSR. It is worth attention that year-round operation of ARC4 ships in NSR waters is not permitted by Russian authorities currently, thus the result of 104 voyages (i.e. year-round sailing) passing through the NSR is unrealistic so far. Nevertheless, the NSR/SCR-combined service can still be economical with 30 voyages (i.e. around 4 months) or even less, given that the bunker price, icebreaker speed and NSR tariffs are sufficiently low, as the bottom-right sub-figure of Figure 6 shows.

4) Economies of scale of ship size also plays an important role in the NSR/SCR-combined route. Bigger ships are more economical than the small ships, whatever other scenarios are.

This research does not include Japanese or Korean ports. It would be interesting to see what happens if Shanghai is replaced by Korean or Japanese ports as the destination in the future. The results might favor the NSR/SCR-combined service more, due to the closer position of those ports to the NSR.

Moreover, if higher rated ice-class ships (say, ARC5) are deployed, then the results may be very different. According to Russian NSR rules, ARC5 ships are allowed to sail the NSR without icebreaker escorts in the summertime under medium sea ice conditions, which saves on the transit fee. However, it must also be noted that the fuel consumption rate and capital cost of ARC5 ships are higher, which leaves the economic feasibility of ARC5 ships difficult to estimate.

In the future, some assumptions in this study can therefore be relaxed. In the short term, factors such as the inclusion of Korean and Japanese ports, multi-port calling services, and higher rated ice-class ships (e.g. ARC5) should be taken into consideration. In the long term, a new Arctic sea ice extent, which may be much smaller than now, and new technologies, such as cheaper ice-class ships with a lower fuel consumption rate, should also be considered. Moreover, we notice the valuation of time also plays a role in influencing carriers' choices, thus it also should be addressed in the future study.

Last but not least, we notice that most new built ships are installed with dual fuel engines now (i.e. LNG ready). As Russia is a major natural gas supplier in the world, and a large share of its gas deposits is located at Arctic region, it is interesting to see what will happen if Russia builds LNG refuelling centres along this route. This issue is worthy of special study in the future.

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