https://dx.doi.org/10.1016/j.trd.2020.102556

LNG-fuelled Container Ship Sailing on the Arctic Sea: Economic and Emission Assessment

Hua Xu[1] Dong Yang[2]*

[1] Centre for Waterborne Transport Economic Policy and Development Strategy Studies, China Waterborne Transport Research Institute

[2] Department of Logistics and Maritime Studies, The Hong Kong Polytechnic University; Shipping Research Centre, The Hong Kong Polytechnic University, Hong Kong

* corresponding author

Abstract

Global warming allows the Northern Sea Route (NSR) to be used as a potential alternative for Asia–Europe shipping. As a clean fuel, liquid natural gas (LNG) has been increasingly used as a marine fuel. This study aims to analyse the economic feasibility and CO2 emission reduction of using LNG-fuelled container ships to sail through the NSR, under the assumption that Sabetta will be developed into an LNG refuelling centre. We establish a shipping profit model and a CO2 emission model and then apply real data to them. Several scenarios are proposed to reflect the different circumstances in practice. We find that a shorter round-trip transit time and appropriate ship size are the most favourable factors for the proposed option. Although data suggests that it is often economically infeasible to deploy LNG-fuelled ships via the NSR, under certain circumstances where it is indeed cost-effective, considerable CO2 emission reduction can be achieved.

Keywords: *Northern Sea Route, LNG-fuelled Ship, Economic Feasibility, CO_2 Emission.*

1. Introduction

The extent of the retreat of Arctic sea ice has made the Arctic Ocean more navigable than ever. There are three main Arctic shipping routes: the Northeast Passage (the Russian sector between Cape Dezhnyov and the Kara Strait or Cape Zhelaniya is called the Northern Sea Route [NSR]), Northwest Passage (through Canadian and Alaskan Arctic waters), and Trans-Arctic Passage (through the central Arctic Ocean). These Arctic shipping routes can considerably shorten the sailing distances between North America, Europe, and East Asia.

Because recent ice conditions in the Northwest Passage and Trans-Arctic Passage have not been suitable for commercial transit navigation, only the NSR has been developed for transit shipping, a voyage where the origin and destination are both outside the Arctic region.

Non-Russian/Soviet commercial transit shipping on the NSR began in 2009, when two German ships sailed from Busan to Rotterdam with one stop at a Russian port, Novy Port, in the middle. Since then, more ships have used the route. In 2013, the volume of cargo transited via the NSR reached a peak of 1.36 million tonnes. In 2014, however, NSR transit traffic drastically decreased, partly because of the Western sanctions on Russia (Zhang *et al*, 2016b). In 2015, the transit cargo volume decreased to less than 40 thousand tonnes, accounting for only 3% of the amount in the peak year. After 2015, the transit cargo volume on the NSR began to increase again and recovered to 491 and 697 thousand tonnes in 2018 and 2019, respectively. The recent main cargos were steel and windmill parts from China to Europe and paper pulp and non-ferrous ores from Europe to China.

As a potential rival to the traditional Suez Canal Route (SCR), the NSR is the main lane between Asian and European ports. These two routes are presented in Figure 1. Because of the large trade volume in manufactured goods between Asian and European countries, the Asia–Europe lane is one of the three busiest container lanes in the world, and the largest container ships are used on it. If the NSR becomes feasible for container shipping, the global container shipping map will change drastically.

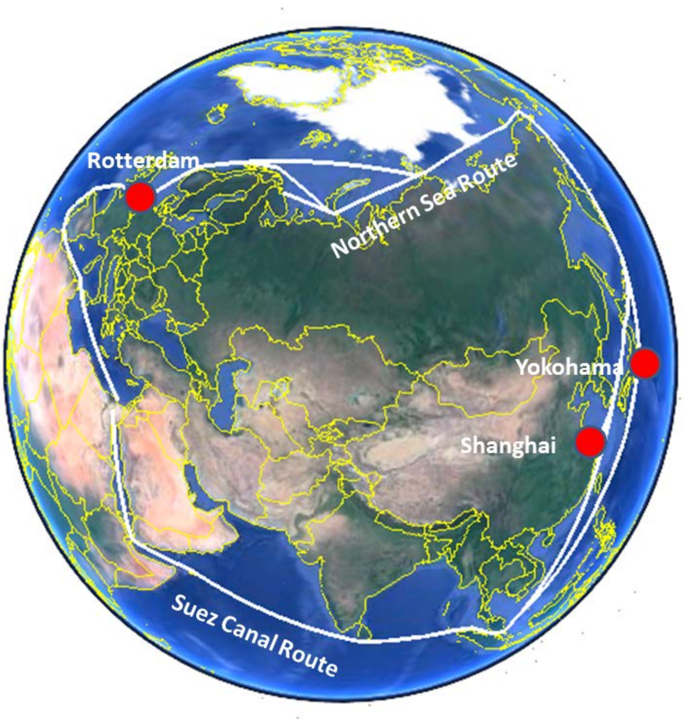

Figure 1 Northern Sea Route (NSR) and Suez Canal Route (SCR)

Source: edited Google Earth screenshot

Although container shipping seems to be promising for the NSR, container ships have rarely observed on the route because of the seasonality and uncertainty of the ice condition along the NSR, as well as the lack of intermediate ports along the route. Nevertheless, *Venta Maersk*, a 3,600-TEU full container ship, passed the NSR in 2018. This is a milestone in Arctic shipping, because she is the first full container ship sailing the entire NSR.

One prominent worldwide trend in the maritime industry is that an increasing number of ships are being adapted to use liquid natural gas (LNG) as a fuel. LNG is clean energy relative to conventional oil-based fuels and thus can significantly reduce the emission of air pollution materials such as SO_X, NO_X, particulate matter (PM), and black carbon. LNG can reduce CO_2 emissions by at least 20% compared to conventional marine fuel (DNV GL, 2015). Although the “methane slip” problem (caused by uncombusted methane from engines) could be a major defect of LNG fuel because of the strong greenhouse capability of methane, high-pressure 2-stroke dual-fuel (LNG and conventional oil fuel) engines, a recently available technology, can significantly mitigate this problem (Lindstad and Rialland, 2020).

LNG has been widely recognised as an alternative marine fuel for the near future. It has become particularly relevant because of the 0.5% sulphur control regulation issued by the International Maritime Organization (IMO), which was enacted at the beginning of 2020. The number of LNG-fuelled ships is increasing rapidly. According to Yoo (2019), as of December 2019, there were 172 operating LNG-fuelled ships worldwide, 20.3% more than 2018. Additionally, 31 LNG-fuelled ships were on order. Notably, the largest LNG-fuelled container ship in the world, 23,000 TEU *CMA CGM Jacques Saade*, was launched in 2019.

In the context of this background, LNG infrastructures are blooming worldwide, especially in the gas-rich Arctic region. The Yamal LNG project, a joint venture run by Russian, Chinese, and French enterprises, is located on the Yamal Peninsula. This Russian Arctic peninsula holds huge natural gas deposits. It is supported by the Yuzhno-Tambeyskoye gas field and designed to output 16.5 million tonnes of LNG annually when fully running, in 2018. Sabetta, the gate-port of this project, exported its first shipment of LNG in December 2017. The LNG will be mostly exported to Asian and European markets. A reasonable expectation is that LNG is cheaper at the place of production. Notably, the free on board (FOB) price of Yamal LNG is much lower than the Northeast Asia-delivered LNG bunker price (discussed in Section 4). Moreover, one of the challenges for LNG fuel is its high well-to-tank (from production plants to consumption places) greenhouse gas emission, which suggests that serious emission occurs in the transport of LNG (Lindstad and Rialland, 2020). Building an LNG refuelling centre at Sabetta to serve the LNG-fuelled ships sailing the NSR is a potential solution for this problem because it shortens the LNG supply chain.

The second LNG project, named Arctic LNG 2, is now under construction. It is located at Utrenneye gas field on the Gyda Peninsula, which is close to Yamal LNG.

This project is also an international joint venture, with Russian, French, Chinese, and Japanese shareholders, and is expected to launch in 2024. After it enters full production, 19.8 million tonnes of LNG will be produced annually, 20% higher than the annual output of Yamal LNG. Because of the new technology of gravity-based structures it applies, the construction of the project will cost approximately USD 21.3 billion, well below that of Yamal LNG, and the production cost per tonne may decrease by more than 30% (Gulf-times, 2018). Therefore, the FOB LNG bunker price in Yamal region will be further reduced after Arctic LNG 2 is fully developed.

In this study, we explore to what extent the FOB Yamal LNG bunker price reductions can economically enable the sailing of LNG-fuelled container ships via the NSR instead of the SCR, and calculate the potential CO_2 emission reduction it can achieve. For comparison, we conceive three options, namely, LN, ON, and OS, defined as follows:

(1) LN indicates LNG-fuelled ships via the NSR with using Sabetta as an LNG refuelling centre;

(2) ON indicates oil-fuelled ships via the NSR; and

(3) OS indicates oil-fuelled ships via the SCR.

We assume that liner operators only use LN or ON during the ice-free season on the NSR but not year-round.

The remainder of this study is arranged as follows. In Section 2, the relevant studies on Arctic shipping and the environmental effects are reviewed. In Section 3, we build a shipping profit model for evaluating the economic feasibility of NSR LNG-fuelled shipping, and an emission model for estimating the CO_2 emissions from ships. In Section 4, an empirical study is conducted with real data to compare the profits and CO_2 emissions among the three options. Section 5 concludes.

2. Literature review

Many studies have focused on the economic feasibility of the NSR by using the traditional SCR as a benchmark. The majority of these works have been reviewed by Lasserre (2014) and Meng *et al* (2016). Many of these works reviewed non-container shipping, such as mineral fertiliser shipping (Schøyen and Bråthen, 2011, Cariou and Faury, 2015), iron ore shipping (Otsuka *et al*, 2013), LNG shipping (Otsuka *et al*, 2013, Raza and Schøyens, 2014), frozen fish shipping (Otsuka *et al*, 2013), and oil tanker shipping (Faury and Cariou, 2016, Zhang *et al*, 2016a). One of the most recent studies was conducted by Theocharis *et al* (2019), who proposed a cost model for product tankers based on the optimal ship speed.

Liner shipping along the NSR has also attracted attention from researchers. Some studies have estimated the cost of a single voyage of the NSR, for example, Arpiainen and Kiili (2006) considered a container shuttle service between Alaska and Iceland; Verny and Grigentin (2009) compared the costs of routes between Shanghai and

Hamburg via the SCR, Trans-Siberian railway, NSR, sea and air route transiting in Dubai, and direct air route; Lasserre (2014) compared the costs of the NSR, the Northwest Passage, and the SCR with Rotterdam, Shanghai, and Yokohama as endpoint ports; and Zhang *et al* (2016a) compared the profits of an NSR voyage with a 5,100 TEU ship to those of an SCR voyage with a 13,900 TEU ship. In other studies, an NSR/SCR-combined service was considered, in which the NSR was used in the navigable window, whereas the SCR was used in other seasons. Among these studies, Liu and Kronbak (2010) compared the cost of a combined service for the SCR between Yokohama and Rotterdam under different scenarios of navigable time of the NSR, NSR fees, and bunker prices; Xu *et al* (2011) proposed a combined service in the NSR with multi-port calling and a one-month navigable window; Omre (2012) studied a combined service between Yokohama and Rotterdam and assumed 14 'ice alternatives' with different combinations of ice conditions over 10 NSR sections; Furuichi and Otsuka (2014) assumed five different scenarios for a navigable window (105, 135, 165, 195, and 225 days); Zhao *et al* (2016) established a two-stage optimisation model for shipping network design with multi-port calling and considered three levels of navigable windows (4, 6, and 8 months); and Xu *et al* (2018) introduced a new approach for simulating the economic performance of a combined service with a dynamic navigable window of the NSR. These studies have evaluated the economic performance of the NSR from various perspectives, but all of them were only concerned with conventional oil-fuelled ships. This study adds a new option to the literature: LNG-fuelled ships on this route.

Arctic shipping can decrease the distances thus reduce fuel consumption considerably; hence, many studies have focused on the environmental impacts of Arctic shipping, especially the assessment of ship emissions. For example, Paxian *et al* (2010) introduced a global bottom-up ship emission algorithm for estimating the fuel consumption, emissions, and vessel traffic densities of Arctic polar routes in 2050; Peters *et al* (2011) used a bottom-up shipping model and detailed global energy market model to construct emission inventories for Arctic shipping and petroleum activities in 2030 and 2050, given estimated sea ice extents; Dalsøren *et al* (2012) evaluated the changes in concentrations of atmospheric pollutants and radiative forcing of short-lived components due to ship emissions from 2004–2030, given the increasing traffic in the Arctic; Winther *et al* (2014) presented a detailed air pollutant emission inventory for ships in the Arctic in 2012, based on satellite automatic identification system data, ship engine power functions, and technologically stratified emission factors; Lindstad *et al* (2016) adopted the concept of Global Warming Potentials (GWP) to describe the warming intensity of many maritime air pollutants in terms of fuels and regions and observed that the net GWP in the Arctic is higher than those of other routes, even when cleaner fuels (e.g. LNG) are used; Yumashev *et al* (2017) studied the comprehensive economic impacts of NSR shipping that cover the environmental benefits from emission reduction, the environmental consequences from the short-lived pollutants (e.g. black carbon) emitted by ships in the Arctic, and the emissions from the additional economic growth incurred by the NSR; Zhu *et al* (2018) calculated the emissions of greenhouse gases and pollutants overall in NSR container shipping and integrated the environmental costs from the emissions into a cost model; Wan *et al* (2018) provided a case study on emission reduction and profit increase by using the NSR; Cariou *et al* (2019) estimated the cost saving and CO_2 emission reduction of container shipping along the NSR by focusing on the impacts of various ice thicknesses over 49 route subzones; Ding *et al* (2020) investigated the effect of a carbon tax (fixed vs progressive schemes) on the economic viability of the NSR against the SCR. These reviewed studies have assessed the environmental impacts of the NSR shipping but have not associated the emission results with the economic feasibility of clean energy applied in NSR shipping. Liner operators are more concerned about the economic performance of the NSR shipping than emission reduction. This study estimates the CO_2 emission reduction of LNG-fuelled shipping on the NSR, based on its economic feasibility.

3. Methodology

In this section, we build models to estimate the shipping profit and CO_2 emission in a container vessel voyage. We define LN as “economically feasible” if it has the highest average voyage shipping profit (AVSP) among the three options.

3.1 Shipping profit model

3.1.1 Average voyage shipping profit

The profit is defined as the difference between the revenue and the cost. The total shipping cost of a container ship comprises five components: fuel cost, capital cost, operating cost, container handling cost, and transit cost of passages (i.e. the Suez Canal toll or NSR icebreaking fee).

The fuel cost, which is determined by the bunker price, the voyage time, and the fuel consumption rate, is formulated as

$$CFV_i = PF_i TS_i F_i,$$

$$i = OS, ON, LN \tag{1}$$

where the subscript i denotes the options OS, ON, or LN hereinafter; CFV_i is the fuel cost in a voyage (US\$); PF_i is the bunker price (US\$/tonne); TS_i is the voyage time at sea (day); and F_i is the fuel consumption rate (tonne/day). The fuel consumption rate is usually considered to be proportional to the cubic of the ship speed (Psaraftis and Kontovas, 2013); thus, F_i is formulated as

$$F_i = FMAX_i \frac{V_i^3}{VMAX_i^3} \tag{2}$$

where $FMAX_i$ is the maximum fuel consumption rate of a ship sailing at its maximum speed (tonne/day), V_i is the ship speed (knot), and $VMAX_i$ is the maximum (or design) speed of a ship (knot). The ship speed is determined by the voyage time at sea and the distance of the voyage:

$$V_i = \frac{L_i}{24TS_i} \quad (3)$$

where L_i is the distance (nautical mile).

Substituting Equations (2) and (3) into Equation (1), we can obtain CFV_i as follows:

$$CFV_i = \frac{PF_i FMAX_i L_i^3}{24^3 TS_i^2 VMAX_i^3} \quad (4)$$

The capital cost is the ship value depreciation and is determined by the new-building price of the ship and her lifetime. Otsuka *et al* (2013) suggested that the economic lifetime of a ship is 10 years, but the data from Shipping Intelligence Network shows that the average age at the demolition time of container ships is 20 years. In this study, we eclectically assume that the lifetime of a ship is 15 years. We adopt straight-line depreciation; thus, the annual depreciated value is 1/15 of the new-building price:

$$CCY_i = \frac{CS_i}{15} \quad (5)$$

where CCY_i is the annual capital cost, and CS_i is the new-building price of a ship.

The operating cost includes repair and maintenance costs, insurance, administration costs, crew wages, and other miscellaneous costs. The estimation of the operating cost varies widely according to different sources, and Zhao *et al* (2016) suggested that it is as high as approximately 80% of the capital cost for a 4,800 TEU container ship. Zhang *et al* (2016a) suggested that this ratio is 56% for a 5,100 TEU ship. Tran and Haasis (2015) indicated that this ratio varies from 16% (for an 11,000 TEU ship) to

52% (for a 1,200 TEU ship). In this study, we adopt the average value of these studies and assume the operating cost to be 50% of the capital cost, as follows:

$$COY_i = 0.5CCY_i \quad (6)$$

where COY_i is the annual operating cost. Because Arctic shipping requires more experienced and skilled seamen, more frequent inspection, and higher insurance, the operating costs of ice-class ships sailing the NSR are higher. We assume that the ratio of CCY_i to COY_i is identical between ice-class and ordinary ships.

Although the number of operating days is less than 365 because some days (often no more than 5 days) are usually spent on maintenance, the ship value depreciation and operating cost still incur during the maintenance days. Therefore, the sum of capital and operating costs for a voyage is

$$CCV_i + COV_i = \frac{CCY_i + COY_i}{365} T = \frac{1.5CS_i}{15 \times 365} T \quad (7)$$

where CCV_i and COV_i are the voyage capital costs and operating costs, respectively; and T is the voyage transit time (day), which includes the times at sea (TS_i) and at port. All options have the same transit time to maintain the ship's schedule.

The container handling cost per voyage, denoted by CHV_i, is charged by ports. It is determined by the quantity of container transported Q_i (TEU) and the handling fee rate HR (US$/TEU):

$$CHV_i = 2Q_iHR \quad (8)$$

Each transported container is loaded once in the origin port and unloaded once in the destination port; thus, it is handled twice in a voyage. Q_i is related to the ship capacity Z_i (TEU) and utilisation rate U_i:

$$Q_i = U_i Z_i \qquad (9)$$

The voyage transit cost of passages, CTV_i, is the NSR icebreaking fee if *i* is *ON* or *LN*, or the Suez Canal toll if *i* is *OS* in each voyage. Notably, although Russia has issued the maximum level of NSR tariffs, in practice, the actual NSR fees are negotiated between shipowners and Atomflot (Russian nuclear icebreaker fleet), and the Suez Canal toll is often quoted as a reference (Otsuka *et al*, 2013, Moe, 2014).

The voyage total shipping cost, CV_i, can then be determined by summing all of the cost items, as follows:

$$CV_i = CFV_i + CCV_i + COV_i + CHV_i + CTV_i$$

$$= \frac{PF_i FMAX_i L_i^3}{24^3 TS_i^2 VMAX_i^3} + \frac{CS_i T}{3650} + 2U_i Z_i HR + CTV_i \qquad (10)$$

The model is used to compare the AVSP (in US$/TEU) of the three options. The voyage shipping revenue, RV_i, is

$$RV_i = Q_i FR = U_i Z_i FR \qquad (11)$$

where *FR* is the freight rate (US$/TEU).

The average voyage revenue and cost are obtained from ship capacity Z_i. The AVSP of option *i* is denoted by $APRV_i$ (US$/TEU) and formulated as

$$APRV_i = ARV_i - ACV_i = \frac{RV_i}{Z_i} - \frac{CV_i}{Z_i}$$

$$= U_i(FR - 2HR) - \left(\frac{PF_i FMAX_i L_i^3}{24^3 TS_i^2 VMAX_i^3} + \frac{CS_i T}{3650} + CTV_i\right)\frac{1}{Z_i}$$

$$= U_i(FR - 2HR) - \left(\frac{g_{1i} PF_i L_i^3}{24^3 TS_i^2} + \frac{g_{2i} T}{3650} + g_{3i}\right) \quad (12)$$

where ARV_i and ACV_i are the average voyage revenue and average voyage cost (US$/TEU), respectively, and g_{1i}, g_{2i}, and g_{3i} are the technological coefficients related to ship size: $g_{1i} \equiv \frac{FMAX_i}{VMAX_i^3 Z_i}$, $g_{2i} \equiv \frac{CS_i}{Z_i}$, $g_{3i} \equiv \frac{CTV_i}{Z_i}$.

3.1.2 Bunker prices threshold

The option LN is economically feasible only if the following two conditions are fulfilled:

$$DIFF_1 \equiv APRV_{LN} - APRV_{ON} > 0 \quad (13)$$

$$DIFF_2 \equiv APRV_{LN} - APRV_{OS} > 0 \quad (14)$$

where $DIFF_1$ and $DIFF_2$ are the differences of average voyage shipping profits (DAVSP) of LN over ON and OS, respectively. By substituting Equation (12) into (13) and (14), in turn, (13) and (14) can be transformed into

$$DIFF_1 = (U_{LN} - U_{ON})(FR - 2HR) + \frac{1}{24^3}\left(\frac{g_{1ON} PF_{ON} L_{ON}^3}{TS_{ON}^2} - \frac{g_{1LN} PF_{LN} L_{LN}^3}{TS_{LN}^2}\right) +$$

$$\frac{(g_{2ON} - g_{2LN})T}{3650} + (g_{3ON} - g_{3LN}) > 0 \quad (15)$$

$$DIFF_2 = (U_{LN} - U_{OS})(FR - 2HR) + \frac{1}{24^3}\left(\frac{g_{1OS} PF_{OS} L_{OS}^3}{TS_{OS}^2} - \frac{g_{1LN} PF_{LN} L_{LN}^3}{TS_{LN}^2}\right) + \frac{(g_{2OS} - g_{2LN})T}{3650}$$

$$+(g_{3OS} - g_{3LN}) > 0 \quad (16)$$

We assume that the time at sea, the ship size and ice-class, and the quantity transported are identical between options ON and LN, namely, U_{LN}=U_{ON}, TS_{LN}=TS_{ON}, Z_{LN}=Z_{ON}, $FMAX_{LN}$=$FMAX_{ON}$, $VMAX_{LN}$=$VMAX_{ON}$, g_{1LN}=g_{1ON}, and g_{3LN}=g_{3ON}, CTV_{LN}=CTV_{ON}. Because LNG is used in the option LN and oil is used in ON and OS, PF_{LN} can be renamed PF_L, and PF_{ON}=PF_{OS} can be renamed PF_O, where PF_O and PF_L represent the bunker prices of oil and LNG fuels, respectively. Thus Inequality (15) can be simplified as

$$PF_L < {PF_{L1}}^* \equiv a_1 PF_O - b_1 \tag{17}$$

where $a_1 \equiv \frac{L_{ON}^3}{L_{LN}^3}$ and $b_1 \equiv \frac{24^3 TS_{LN}^2 (g_{2LN} - g_{2ON})T}{3650 g_{1LN} L_{LN}^3}$.

Similarly, Inequality (16) can be changed into

$$PF_L < {PF_{L2}}^* \equiv a_2 PF_O - b_2 \tag{18}$$

where $a_2 \equiv \frac{g_{1OS} TS_{LN}^2 L_{OS}^3}{g_{1LN} TS_{OS}^2 L_{LN}^3}$ and

$$b_2 \equiv \frac{24^3 TS_{LN}^2}{g_{1LN} L_{LN}^3}\left[(U_{OS} - U_{LN})(FR - 2HR) + \frac{(g_{2LN} - g_{2OS})T}{3650} + (g_{3LN} - g_{3OS})\right].$$

PF_{L1}^* and PF_{L2}^* are the two thresholds of PF_L that enable LN to be more economical than ON and OS, respectively. The LNG bunker price threshold PF_L^* is

$${PF_L}^* = \min({PF_{L1}}^*,\ {PF_{L2}}^*) \tag{19}$$

If and only if $PF_L < PF_L^*$, LN is the economically feasible option.

By contrast, the threshold of oil bunker price can be formulated as a function with respect to the ratio of LNG bunker price to oil bunker price, namely, d=PF_L/PF_O.

Given that the baseline of LNG bunker price is equal to the oil bunker price, the discount of LNG bunker price is 1-*d*. Inequalities (17) and (18) are transformed into

$$PF_O > PF_{O1}{}^{*} \equiv \frac{b_1}{a_1 - d} \quad (20)$$

$$PF_O > PF_{O2}{}^{*} \equiv \frac{b_2}{a_2 - d} \quad (21)$$

$$PF_O{}^{*} = \max(PF_{O1}{}^{*},\ PF_{O2}{}^{*}) \quad (22)$$

where $PF_{O1}{}^{*}$ and $PF_{O2}{}^{*}$ are the two thresholds of PF_O that enable LN to be more economical than ON and OS, respectively, and $PF_O{}^{*}$ is the oil bunker price threshold. If and only if $PF_O > PF_O{}^{*}$, LN is economically feasible.

The thresholds of bunker prices are illustrated in Figure 2, where the horizontal axis represents the bunker price of oil fuel and the vertical axis represents that of LNG fuel. The lines representing $PF_{L1}{}^{*}$ and $PF_{L2}{}^{*}$ intersect at Point A. If LN is an economically feasible option, PF_L should be lower than both of them, which is depicted as the grid polygon in the figure, surrounded by the broken line A'AA" ($PF_L{}^{*}$) and the two axes. The lengths of lines OB and OA' indicate the oil bunker price thresholds $PF_{O1}{}^{*}$ and $PF_{O2}{}^{*}$, respectively, when the LNG bunker price is zero.

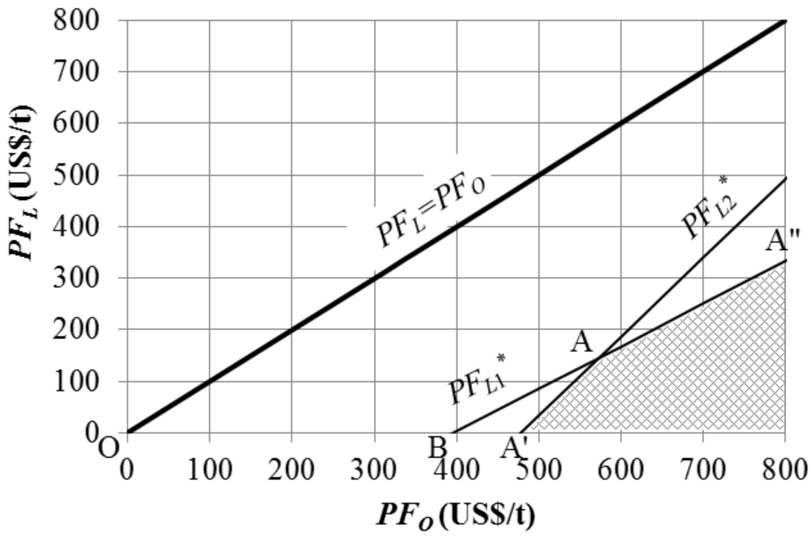

Figure 2 Relations between LNG bunker price thresholds PF_{L1}^*, PF_{L2}^*, and oil bunker price PF_O

3.2 Emission model

The main types of gas emitted from a ship's combustion process are CO_2, SO_x, NO_x, and PM. The LNG-fuelled ship can reduce NO_x emissions by 85%–90% and can nearly eliminate SO_x and PM emissions, compared to conventional fuel oil (IMO report, 2016). By contrast, the reduction of CO_2 is relatively minor and ranges between 5% and 30% (Bouman *et al*, 2017). Because LNG fuel has absolute advantages over conventional fuel oil in NO_x and SO_x emissions, whereas the reduction in CO_2 is relatively modest, in this study, we only focus on the CO_2 emission comparison among the three options.

The CO_2 emission in option *i* is expressed as

$$EM_i = EF_i \frac{FMAX_i L_i^3}{24^3 TS_i^2 VMAX_i^3} \quad (23)$$

where EM_i is the CO_2 emissions per voyage (tonne), and EF_i is the CO_2 emission factor that indicates the tonnes of CO_2 emitted from each tonne of fuel burnt in option *i*. According to Peters *et al* (2011), the average CO_2 emission factor of residual fuel oil is 3.13; thus, we set EF_{ON}=EF_{OS}=3.13. DNV GL (2015) in its technology report "Focus - LNG as Ship Fuel" suggested that CO_2 emission per tonne of LNG fuel is set to be 20% lower than that of conventional oil fuel, which is close to the value suggested by Bouman *et al* (2017); thus, we set EF_{LN}=3.13*0.8=2.504. The fuel consumption rates of oil-fuelled and LNG-fuelled ships are assumed to be identical because DNV GL (2019) indicated that gas-fuelled engine systems have approximately the same efficiency as conventionally fuelled systems.

The average CO_2 emission per TEU in option *i* is therefore determined as follows:

$$AEM_i = \frac{EM_i}{Z_i} = EF_{\mathrm{i}} \frac{g_{1i} L_i^3}{24^3 TS_i^2} \tag{24}$$

The emission reduced by LN from OS is

$$AEM_{OS} - AEM_{LN} = \frac{1}{24^3}\left(\frac{EF_{OS} g_{1OS} L_{OS}^3}{TS_{OS}^2} - \frac{EF_{LN} g_{1LN} L_{LN}^3}{TS_{LN}^2}\right) \tag{25}$$

4. Empirical Study

In this section, we compare the shipping profits and CO_2 emissions among three options (LN, ON, and OS) by applying the real data of sample ships, distances between ports, and fuel prices to the profit and emission models.

To achieve this goal, we must first propose assumptions and scenarios by considering the variation of factors, to reflect the different circumstances in the real world. Then, we discuss the economic feasibility of LN, and its potential in reducing CO_2 emission.

4.1 Assumptions

We provide the assumptions of this study as follows:

(1) Because of the economies of scale in ship size, container operators always employ the largest ships on the SCR; thus, we assume that the largest ships are always used on the SCR. For the two NSR options, we assume that the same ship sizes are employed, and the size is optimised in this empirical study to maximise the DAVSP of LN over OS, $DIFF_2$, under the cases that LN is economically feasible.

(2) In this study, the compared NSR voyages are assumed to be conducted in the ice-free season when the Arctic sea ice extent is minimal (approximately from late August to early October). According to recent Arctic sea ice charts from the National Snow and Ice Data Center, it is common that the entire NSR is ice-free during this season.

(3) Ice-class 1A (Finnish-Swedish Ice Class Rules) or ARC4 (Russian Maritime Register of Shipping, Rules 2007) ships are assumed to be deployed in two NSR options. This ice-class level is the most widely used in Arctic or sub-Arctic ice-infected waters. Compared to ordinary ships, ice-class ships consume more fuel in open water, and the ice-strengthened measures cost more to build; thus, we compare

the fuel consumption rates and new-building prices between ice-class 1A (or ARC4) ships and their ordinary peer ships. By regressing the data from the Shipping Intelligence Network, we find that the ratio of fuel consumption rate of oil-fuelled 1A ships to that of ordinary ships ($FMAX_{ON}/FMAX_{OS}$) is 1.106, and the ratio of new-building prices of these two ship types (CS_{ON}/CS_{OS}) is 1.123. Erikstad and Ehlers (2012) suggested that the capital cost of a 1A ship is 9.5% higher than that of an ordinary ship, which is close to our result. Therefore, we set these two ratios to 1.1 in this study.

(4) According to *Rules of navigation in the water area of the Northern Sea Route* issued by Russia in 2013, ARC4 ships can independently sail the NSR from July to November if there is no ice or the ice condition is light. Therefore, we assume that the ice-class ships sail the NSR without icebreaker escorting during the ice-free season and the NSR icebreaking fee is null: $CVT_{LN}=CVT_{ON}=0$.

(5) The price of conventional oil fuel is based on the average cost of marine gas oil (MGO) and 380 cst fuel oil in Singapore, and this is close to the Northeast Asia-delivered LNG price; thus, we set $PF_L=PF_O$ as the no discount baseline in our theoretical analysis framework. However, according to the Clipper Data daily LNG report in July and August 2018, the FOB LNG price from Yamal LNG at Sabetta, which is anticipated as the LNG refuelling location on the NSR, is approximately 80% of the Northeast Asia-delivered LNG price. Therefore, we set the base level of the

FOB Yamal LNG bunker price to be 80% of the oil fuel price in the empirical analysis in Section 4.3.

(6) Compared to a peer oil-fuelled ship, an LNG-fuelled ship has a more sophisticated design, which induces higher costs. The capital and operation costs for LNG-fuelled ships vary widely for different ship types. However, recent advancements in relevant technologies have made them cheaper. In May 2017, Sovcomflot (a Russian shipping company) ordered four LNG-fuelled 114,000 deadweight tankers at US$60 million each; they were 27% more expensive than peer oil-fuelled ships. In a Bloomberg interview with DNV GL, LNG-fuelled ships were said to be 10%–25% more expensive than comparable vessels running on fuel oil (Bloomberg, 2015). An earlier report from Wärtsilä, a main marine engine manufacturer, suggested that the sum of the annual capital, lubrication oil, maintenance, and selective catalytic reduction system operation costs (conventional ships only) of an LNG-fuelled ship is approximately 15% higher than that of a conventional ship using MGO as fuel (Wärtsilä, 2011). Exact data on the capital and operating costs of LNG-fuelled ships remain very scarce. Considering all the aforementioned sources, in this study, we assume that the capital and operating costs of an LNG-fuelled ship are both 20% higher than those of a conventional ship, namely, $g_{2LN}=1.2g_{2ON}$.

(7) We assume that in LN, the ship will travel north of Novaya Zemlya because of the shorter distance to European ports. The location of Sabetta and the paths are presented in Figure 3.

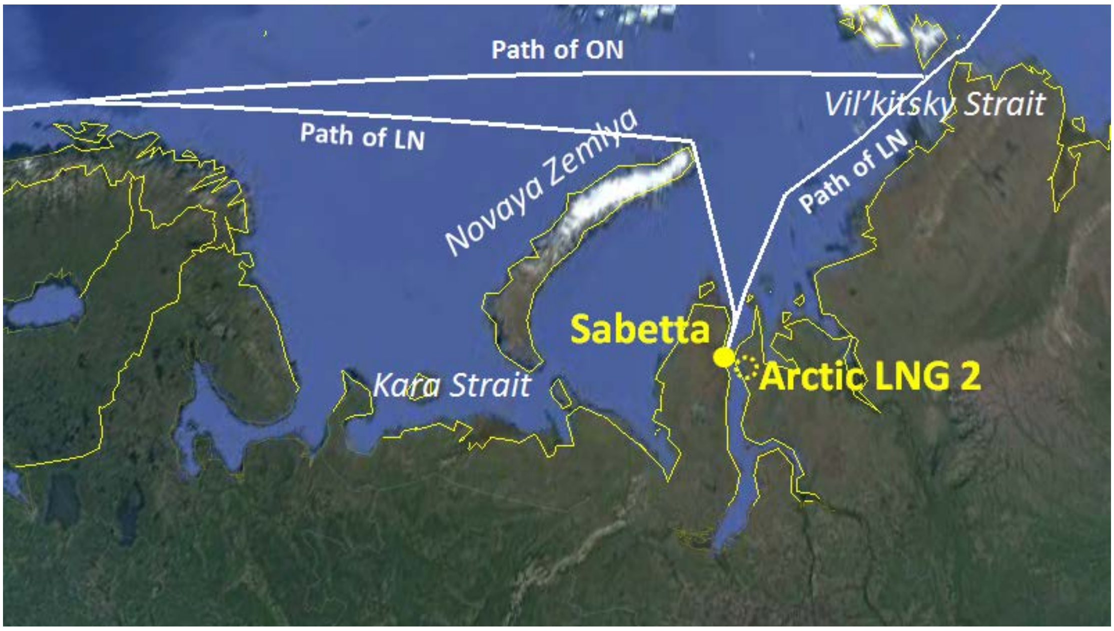

Figure 3 NSR paths near Sabetta

Source: edited Google Earth screenshot

(8) Two port ranges are considered: the East Asian port range and the Northwest European port range. We assume that the former range stretches from Yokohama in the north to Hong Kong in the south, and the latter range stretches from Hamburg in the north to Le Havre in the south. The container services of both routes are considered a "multi-port calling" service, which indicates a series of ports are called during the voyage. We use the longest distances between the pair of ports in each port range as the distances of three options. The distances are measured on Google Earth: L_{OS}=11526 nautical miles (between Yokohama and Hamburg), L_{ON}=8499 nautical miles (between Hong Kong and Le Havre), and L_{LN}=9038 nautical miles (also between Hong Kong and Le Havre but with calling at Sabetta). Moreover, referring to the current Asia–Europe container services of several main liner operators (including

Maersk, MSC, CMA CGM, and COSCO), we find that on average, five ports are called on a one-way voyage within each range.

(9) Although the NSR shortens the distance considerably, the lack of intermediate ports may lead to the loss of revenue. If an Asia–Europe container service shifts from the SCR to the NSR, the cargos between Southeast Asia and Northwest Europe will be skipped. By analysing the bilateral trade data of SITC Category 5-9 commodities (roughly equivalent to manufactures) in 2018 from UN Comtrade Database, we find that Southeast Asia–Northwest Europe trade accounts for approximately 15% of Far East (East and Southeast Asia)–Northwest Europe trade. Therefore, we set both capacity utilisation rates U_{LN} and U_{ON} to be 15% lower than U_{OS}.

(10) Based on Shanghai Containerized Freight Index, the average monthly freight rate from Shanghai to Europe in 2016–2018 is 793.2 US$/TEU; thus, we set the westbound freight rate of the Asia–Europe lane to be 800 US$/TEU. Referring to the bilateral freight rate data from Sea & Air Shipper Insight (published by Drewry) and the container trade data from Shipping Review and Outlook (published by Clarksons), the ratio of freight rates between two directions is approximately the same as that of container trade volume. As in 2016–2019, the eastbound container trade volume of this lane is roughly half of the westbound, and the eastbound freight rate is set to 400 US$/TEU. The ratio of the westbound to eastbound capacity utility rate of an Asia–Europe container service is 1:0.5.

(11) The container handling fee is assumed to be 100 US$/TEU, as suggested by Furuichi and Otsuka (2014).

4.2 Scenarios

In addition to the aforementioned assumptions, we propose several scenarios by considering the changes of two important factors: ship size and round-trip transit time of a service. The ship size determines many other parameters, for example, maximum ship speed, maximum fuel consumption rate, and new-building price. The round-trip transit time of a service is twice as long as the transit time per one-way voyage, T_i.

(1) Seven container ship size levels are considered on the NSR: 4000, 6000, 8000, 10000, 12000, 14000, and 16000 TEU. The technical parameters of sample ships are listed in Table 1. On the SCR, only 16,000 TEU ships are assumed to be used, which is close to the average ship size employed on this lane currently. Most Arctic studies assume that sizes of container ships sailing the NSR are smaller than 5,000 TEU (e.g. 3,800 TEU by Omre [2012], 4,000 TEU by Verny and Grigentin [2009] and Furuichi and Otsuka [2014], 4,300 TEU by Liu and Kronbak [2010], 4,500 TEU by Lasserre [2014], and 4,800 TEU by Zhao *et al* [2016]). This is because these studies have assumed that the ships pass a coastal route through shallow water in the Sannikov Strait (13 m deep). In this study, the NSR route is assumed to be north of the New Siberian Islands because of the minimal ice condition in the ice-free season; thus, the Sannikov Strait is bypassed, and larger ships can be used.

Table 1 Scenarios of container ship size and their properties

Ship size (TEU capacity)	**4000**	**6000**	**8000**	**10000**	**12000**	**14000**	**16000**
Sample ship	Xin Nan Sha	E.R. France	OOCL Ningbo	COSCO Kaohsiung	MSC Ivana	MSC Alexandra	CMA CGM Marco Polo
Max speed (kt)*	24.5	26	26	25	24	24.1	24.1
Max fuel consumption rate (t/d) *	133	200	248	250	250	262.2	288
New-building price adjusted to 2015 (million US$) *	44	60	79	96	110	130	147
Gross tonnage (t) *	41482	66289	89097	115776	131771	153115	175343
Suez Canal toll (million US$) **	0.240	0.335	0.406	0.487	0.533	0.594	0.658
g_{1OS} (10^{-6})	2.261	1.897	1.764	1.600	1.507	1.338	1.286
g_{2OS}	11000	10000	9875	9600	9167	9286	9188
g_{3OS}	60.0	55.8	50.8	48.7	44.4	42.5	41.1
g_{2OS}/g_{1OS} (10^{-6})	4865.2	5272.8	5598.8	6000.0	6082.6	6940.0	7144.6

Source: * Shipping Intelligence Network; ** Based on canal tariffs issued by Suez Canal Authority.

(2) Three round-trip transit times are set as 84, 77, and 70 days. The most common round-trip transit time of an Asia–Europe service is 84 days with 84/7=12 ships deployed. Services with a 77- or 70-day round trip also exist, and they require 11 or 10 ships, respectively. In this study, we assume the voyage transit time T under the three scenarios is 42, 38.5, and 35 days, respectively. By investigating the major liner operators, we find that a typical Asian-Europe service has 10 port-calls in East Asia and Northwest Europe, and four port-calls in the middle (e.g. Singapore); thus, the port-call total is 14. Each call takes on average approximately 1 day at port; thus, $TS_{OS}=T-7$. Because no commercial port exists along the NSR, $TS_{ON}=TS_{LN}=T-5$.

According to the assumptions, DAVSP in Inequalities (15) and (16) can then be numerically expressed as

$$DIFF_1 = \frac{(4.4409PF_O - 5.3405PF_L) * 10^7 g_{1ON}}{(T-5)^2} - 5.4795 * 10^{-5} g_{2ON} T \tag{26}$$

$$DIFF_2 = -11.366 + \left(\frac{142.4372PF_O}{(T-7)^2} - \frac{5.3405 * 10^7 g_{1LN} PF_L}{(T-5)^2}\right) + 2.7397 * 10^{-4}(9187.5 - g_{2LN})T \tag{27}$$

4.3 Result discussion

Based on the assumptions and scenarios, our comparison of the three options is presented in this section. First, we discuss the impacts of round-trip transit time and NSR ship size on the results of DAVSP and bunker price thresholds, to understand how the results change under different scenarios. Second, we analyse the economic feasibility of LN. Finally, the CO_2 emission reduction is calculated.

4.3.1 Impacts of round-trip transit time and NSR ship size

The round-trip transit time, twice as long as the voyage transit time *T*, affects the LNG bunker price thresholds PF_{L1}^* and PF_{L2}^*. According to Inequalities (17) and (18), *T* changes in the same direction as b_1 and b_2, and opposite direction against a_2. A larger *T* will thus lead to a smaller PF_{L1}^* or PF_{L2}^*. This indicates that for a longer round trip, a larger extent of LNG bunker price discount is necessary to make LN economically feasible.

The transit time also affects the DAVSP. Based on Inequalities (15) and (16), $PF_O L_{ON}^3$-$PF_L L_{LN}^3$>0 is a necessary condition for $DIFF_1$>0. Under this condition, a larger T always leads to a larger TS_{ON} or TS_{LN}, leading to a lower $DIFF_1$. Similarly, a larger T can also lead to a lower $DIFF_2$. This means that when slow steaming is adopted, a longer round-trip transit time will make LNG-fuelled container shipping on the NSR less likely to be economically feasible.

The NSR ship size affects the thresholds of bunker prices and the feasibility of LN indirectly through technological coefficients g_{1i} and g_{2i}. Table 1 shows that g_{1i} and g_{2i} both decline with an increase of the ship size, except that g_{2i} is the lowest at Z_i=12,000 TEU. By contrast, the ratio g_{2i}/g_{1i} changes in the same direction as the ship size. From Inequalities (17) and (18), we observe that the decreasing of NSR ship size will lower b_1 and thus increase the threshold PF_{L1}^*; the decreasing of NSR ship size will lower a_2, and thus decrease the slope of the curve of PF_{L2}^*; however, the effect on b_2 is undetermined. Therefore, the composite effect of NSR ship size on the threshold of LNG bunker price PF_L^* is also undetermined.

The impact of NSR ship size on DAVSP can be observed from Equations (26) and (27). If $DIFF_1$>0, when NSR ship size decreases, g_{1ON} will increase but g_{2ON}/g_{1ON} will decrease; thus, $DIFF_1$ will increase. This suggests that a smaller ship size on the NSR can enlarge the profit advantage of LNG-fuelled ships over oil-fuelled ships. However, a smaller ship size will lead to larger g_{1LN} and g_{2LN} (except at Z_i=12,000 TEU) and make $DIFF_2$ decline, which shrinks the profit advantage of LN over OS.

Consequently, a trade-off exists among the three options: deploying smaller ships to make LNG-fuelled shipping more economical than oil-fuelled shipping on the NSR, or deploying larger ships to make the NSR more economical than the SCR. This trade-off is illustrated in Figure 4, which shows the thresholds PF_L^* under two round-trip transit times (84 and 70 days) and three NSR ship sizes (4000, 10000, and 16000 TEU). The lower-right areas beneath the thin lines indicate the economically feasible spaces of bunker prices for LN under the corresponding ship sizes. In the left panel, the line of 10,000 TEU has a larger feasible space than that of 4,000 or 16,000 TEU; thus, 10,000 TEU is more economical than 4,000 and 16,000 TEU in this case. This implies that an optimal NSR ship size exists, and it varies with the round-trip transit time and bunker prices.

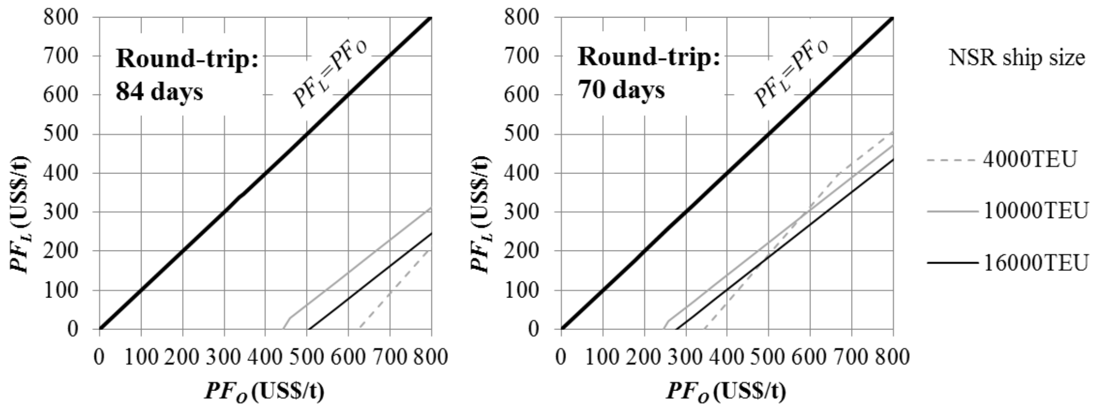

Figure 4 LNG bunker price threshold PF_L^* under 3 NSR ship sizes and 2 round-trip transit times

4.3.2 Economic feasibility of LN

In Figure 5, we plot the optimal NSR ship size and the corresponding DAVSP of LN over OS (*DIFF*$_2$) and under that ship size. This figure considers all three round-trip transit times. The black lines reflect different values of *d* (ratio of LNG bunker price to oil bunker price). In the left three panels, the grey areas indicate the positive DAVSP, or called “feasible spaces” of LN; the white areas are “infeasible spaces” of LN. From the grey areas traversed by the black lines, we can understand the DAVSP under different oil bunker prices and LNG bunker price discounts. Similarly, in the right three panels, the grey areas indicate the optimal NSR ship sizes.

The left-side panels of Figure 5 imply that a shorter round-trip transit time will lead to a higher profit of LN. Given that the other conditions are unchanged, in the feasible space, a higher oil bunker price is always favourable for LN. The LNG bunker price threshold PF_L^* (represented by the borderline between feasible and infeasible areas) is closely related to the oil bunker price PF_O: a higher PF_O will lower the discount threshold PF_L^*. For example, for the 70-day round trip, when PF_O=400 US$/t, a discount no less than 59.4% (*d*=40.6%) is necessary to ensure the economic feasibility of LN, and when PF_O=800 US$/t, the discount threshold decreases to 36.5% (*d*=63.5%).

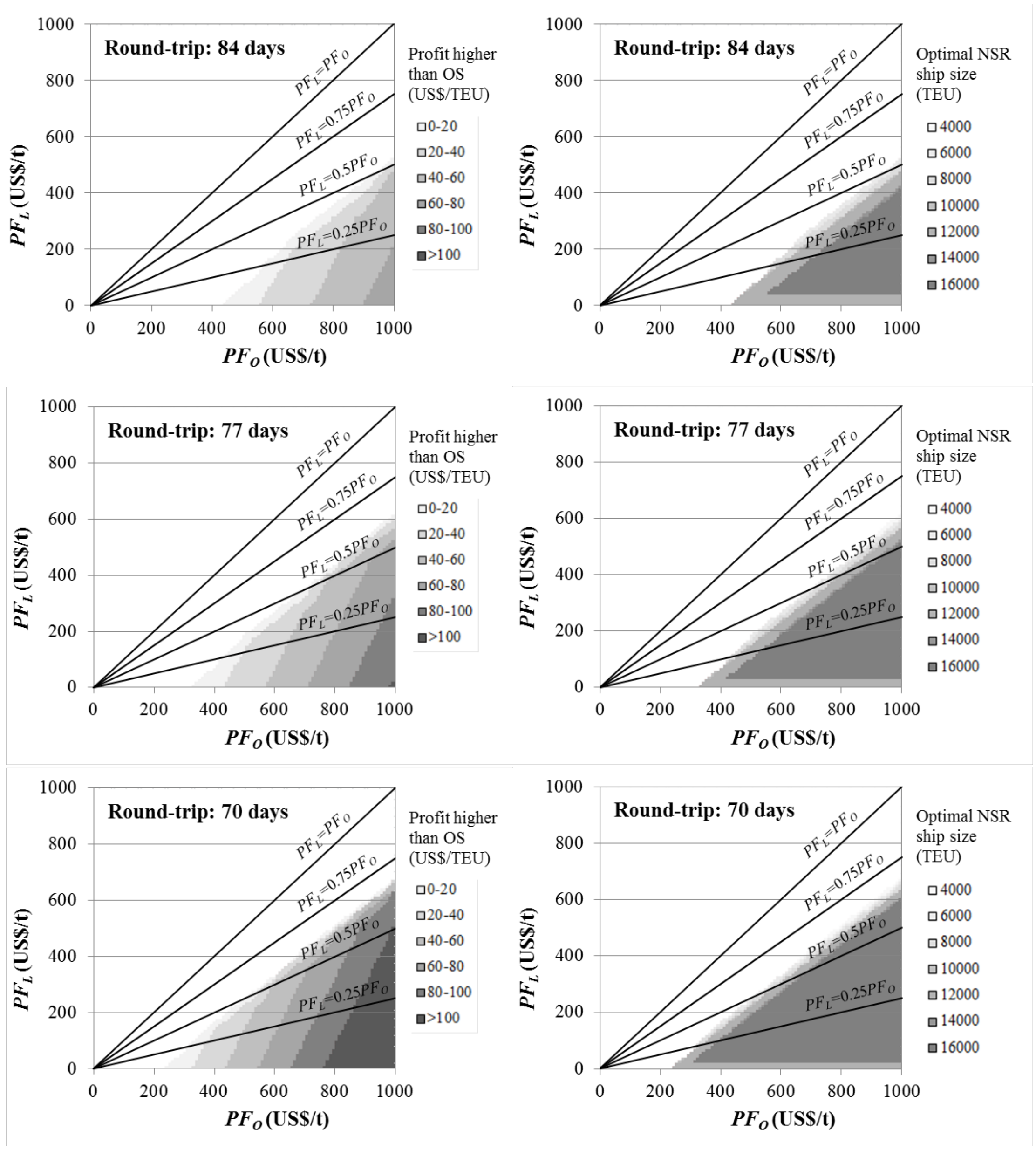

Figure 5 Difference of AVSP of LN over OS and corresponding optimal NSR ship size

From each panel on the right side in Figure 5, the darkest grey triangle area indicates that deploying the largest ships (16,000 TEU) on the NSR is the best choice under the corresponding combination of two bunker prices PF_L and PF_O. In the lighter grey area surrounding the darkest triangle, a smaller NSR ship size is optimal. This finding reflects the trade-off of ship size choice in LN against OS and ON, simultaneously depicted in Section 4.3.1. This lighter grey area becomes narrower when the round-trip transit time decreases, implying that larger LNG-fuelled ships with a short transit time are preferred on the NSR.

The points on the borderline between feasible space (grey area) and infeasible space (white area) in Figure 5, which indicate the threshold of bunker prices (PF_L^* or PF_O^*), can be calculated from Inequalities (17)–(22). We define $d^*=PF_L^*/PF_O$ to be the threshold of bunker price ratio d. LN can be economically feasible below d*. d* and its corresponding optimal NSR ship sizes are listed in Table 2. The oil bunker price higher than 800 US$/t is excluded because this price is much higher than the reasonable range in reality. These points imply the feasible thresholds of bunker prices for the option LN. For example, in an 84-day round trip, to make LN economically feasible, when the oil bunker price is 600 US$/t, the discount of LNG bunker price should not be lower than 71.9% (d=28.1%), which is unreasonably high; if the discount declines to 60% (d=40%), the oil bunker price should be higher than 721 US$/t, which is also much higher than the recent practical oil bunker price. In summary, for a container service with a round-trip of 84 days, it is generally uneconomical to deploy LNG-fuelled ships on the NSR. Nevertheless, for a shorter round trip, for example, of 70 or 77 days, the option LN is more likely to be feasible.

Table 2 Threshold of bunker price ratio and corresponding optimal NSR ship size

84-day round trip (*T*=42)			**77-day round trip (*T*=38.5)**			**70-day round trip (*T*=35)**		
PF_O (US$/t)	d^* (%)	Optimal NSR ship size (TEU)	PF_O (US$/t)	d^* (%)	Optimal NSR ship size (TEU)	PF_O (US$/t)	d^* (%)	Optimal NSR ship size (TEU)
432	0.0	12000	324	0.0	12000	236	0.0	12000
484	10.0	10000	364	10.0	10000	265	10.0	10000
500	12.4	10000	400	16.7	10000	300	18.5	10000
550	20.0	8000	416	20.0	8000	307	20.0	10000
600	28.1	8000	467	30.0	8000	340	30.0	8000
621	30.0	8000	500	36.4	6000	395	40.0	6000
700	38.7	6000	542	40.0	6000	400	40.6	6000
721	40.0	6000	600	44.2	6000	500	49.1	6000
800	44.3	6000	700	49.8	6000	514	50.0	6000
			705	50.0	6000	600	54.8	6000
			800	53.9	6000	679	60.0	4000
						700	60.7	4000
						800	63.5	4000

As mentioned in Assumption (5), the FOB price of the Yamal LNG price is 20% lower than the oil fuel price, which means the baseline of the FOB Yamal LNG price is *d*=0.8. Due to the new project of Arctic LNG 2 under construction, the LNG price in this region is expected to decrease further. If the future FOB Yamal LNG price decreases to half of its recent level, then *d* will decrease to 0.4. The monthly average value of the MGO and 380 cst fuel oil prices in the last decade fluctuated between 200 and 800 US$/t. In Figure 6, we plot the DAVSP and optimal NSR ship size within the practical ranges of PF_O (200–800 US$/t) and *d* (0.4–0.8) for a 70-day round-trip, indicated by the area surrounded by the dashed line. We find observe that the economically feasible space of LN (grey area) within the practical ranges is very limited.

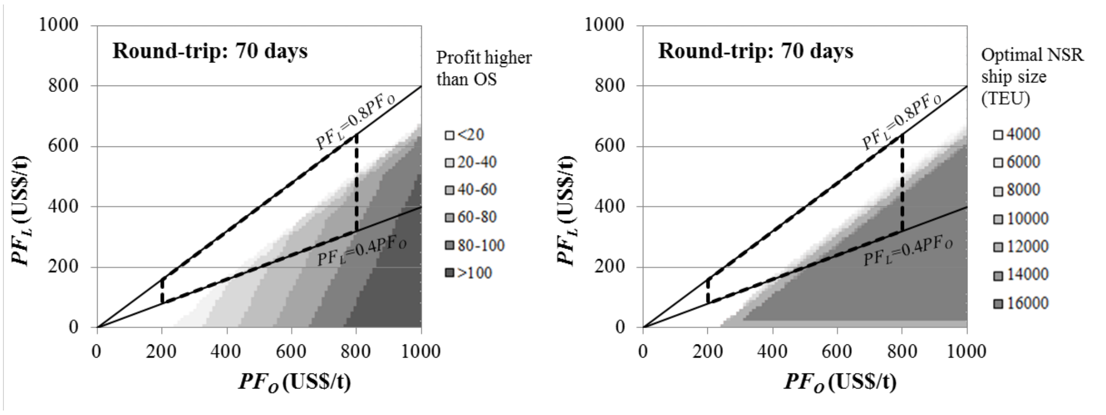

Figure 6 Difference in AVSP of LN over OS and corresponding optimal NSR ship size under practical oil bunker price and LNG bunker price discount for a 70-day round trip

In Table 3, we list the results of the DAVSP and optimal NSR ship size within the practical space depicted in Figure 6. The percentage by which the AVSP of LN is higher than that of OS is also calculated. We find that with the recent oil bunker price fluctuating approximately 400 US$/t, the only feasible scenario for LN is a 70-day round-trip service with the LNG bunker price as 50% of the recent FOB Yamal LNG price (d=0.4), and the DAVSP of LN over OS is 3 US$/TEU, or 2%, which is marginal.

Table 3 Difference in AVSP and optimal NSR ship size of LN under practical oil bunker price and LNG bunker price discount

Round-trip (day)	***d* (%)**	**Profit of LN higher than OS (US$/TEU)**					**Optimal NSR ship size (TEU)**				
		Oil bunker price PF_O (US$/t)					Oil bunker price PF_O (US$/t)				
		400	500	600	700	800	400	500	600	700	800
84	40	-	-	-	-	13.2 (12.0)	-	-	-	-	8000
77	40	-	-	12.0 (9.6)	36.3 (32.6)	50.9 (52.4)	-	-	8000	12000	16000
	45	-	-	-	26.0 (23.3)	44.4 (45.7)	-	-	-	10000	12000
	50	-	-	-	-	26.0 (26.7)	-	-	-	-	8000
70	40	3.0 (2.0)	31.9 (24.5)	49.3 (44.1)	64.1 (68.5)	78.9 (104.6)	6000	12000	16000	16000	16000
	45	-	16.7 (12.8)	44.6 (39.9)	61.2 (65.4)	75.6 (100.2)	-	8000	14000	16000	16000
	50	-	-	40.2 (36.0)	58.2 (62.2)	72.2 (95.7)	-	-	12000	16000	16000
	55	-	-	-	50.0 (53.4)	66.1 (87.7)	-	-	-	12000	14000
	60	-	-	-	2.7 (2.9)	41.8 (55.5)	-	-	-	4000	8000

Note: Numbers in brackets are the percentages of the profit of LN higher than OS.

4.3.3 CO_2 emission reduction of LN

Finally, we investigate the CO_2 emission reduction of the option LN compared to OS, based on Equation (25), and find that the CO_2 emission reduction depends on the distance, ship size, and transit time (ship speed). The bunker prices PF_O and PF_L also affect CO_2 emission but are through their relations to the optimal NSR ship size: At each combination of PF_O and PF_L in the feasible space in Figure 5, an optimal NSR ship size exists, which also determines the CO_2 emission reduction. We calculate the CO_2 emission reduction under each scenario and list the results in Table 4.

Table 4 CO_2 emission reduction of LN compared to OS for NSR ship sizes

NSR ship size (TEU)	84-day round trip (T=42)		77-day round trip (T=38.5)		70-day round trip (T=35)	
	CO_2 emission reduction (t/TEU)	As %	CO_2 emission reduction (t/TEU)	As %	CO_2 emission reduction (t/TEU)	As %
4000	0.121	33.2	0.153	34.0	0.199	35.0
6000	0.160	44.0	0.201	44.7	0.259	45.5
8000	0.174	47.9	0.218	48.5	0.280	49.3
10000	0.192	52.8	0.240	53.3	0.307	54.0
12000	0.202	55.5	0.252	56.0	0.322	56.7
14000	0.220	60.5	0.274	61.0	0.350	61.5
16000	0.226	62.0	0.281	62.5	0.358	63.0

We also calculate the practical CO_2 emission reduction based on the feasible cases by considering the practical range of oil bunker price and LNG bunker price discount. The results are listed in Table 5.

Table 5 CO_2 emission reduction of LN compared to OS under practical oil bunker price and LNG bunker price discount

Round -trip (day)	d (%)	CO_2 emission reduction (t/TEU)					As percentage of OS (%)				
		Oil bunker price PF_O (US$/t)					Oil bunker price PF_O (US$/t)				
		400	500	600	700	800	400	500	600	700	800
84	40	-	-	-	-	0.174	-	-	-	-	47.9
77	40	-	-	0.218	0.252	0.281	-	-	48.5	56.0	62.5
	45	-	-	-	0.240	0.252	-	-	-	53.3	56.0
	50	-	-	-	-	0.218	-	-	-	-	48.5
70	40	0.259	0.322	0.358	0.358	0.358	45.5	56.7	63.0	63.0	63.0
	45	-	0.280	0.350	0.358	0.358	-	49.3	61.5	63.0	63.0
	50	-	-	0.322	0.358	0.358	-	-	56.7	63.0	63.0
	55	-	-	-	0.322	0.350	-	-	-	56.7	61.5
	60	-	-	-	0.199	0.280	-	-	-	35.0	49.3

In summary, for a 70-day round-trip service, CO_2 emission per TEU can be reduced by more than 0.3 tonnes, when the NSR ship size is larger than 10,000 TEU. However, on a 77-day round-trip service, the emission reduction per TEU is between 0.2 and 0.3

tonnes. If the round-trip time is 84 days, such as those of most current Asia–Europe container services, the emission reduction will be less than 0.2 tonne per TEU, at the highest practical oil bunker price.

5. Conclusion

This study discusses the economic feasibility and potential CO_2 emission reduction for a container service using LNG-fuelled ships on the NSR (named “LN”), benchmarking oil-fuelled shipping on the SCR (named “OS”), or on the NSR (named “ON”). We assume that Sabetta, the gate-port of Yamal LNG, can be developed into an LNG refuelling centre. The option LN is economically feasible only if it has the highest AVSP among the three options.

We establish a profit model for estimating the shipping profit of a container service, and an emission model for calculating CO2 emission. The real data of the ships, route information, and bunker prices are collected and applied to the models. To address the complexities in reality, multiple scenarios are proposed and analysed by considering variations in the factors, including seven levels of ship sizes deployed on the NSR, and three levels of the length of round-trip times. The results of this empirical study reveal the following findings:

(1) Smaller ships make LN more advantageous over ON by curbing the capital and operating costs but make it more disadvantageous against OS, in which economies of

scale in ship size are achieved by larger ships. Given round-trip transit time and bunker prices, an optimal ship size for the option LN exists.

(2) A shorter round-trip transit time can make the option LN more economically feasible because a shorter round-trip transit time is in line with a faster ship speed that substantially increases the fuel consumption. In addition, it leads to lower capital and operating costs because of shorter voyage times. For LN, its advantage in fuel cost offsets its loss in capital and operating cost.

(3) In the current circumstance, the option LN is hardly economically feasible, unless the round-trip transit time is 70 days. The additional cost of an LNG-fuelled ship and the detour to the proposed Sabetta LNG refuelling centre make this option less competitive.

(4) LN can reduce CO_2 emission significantly against OS. Practically, the option LN can reduce CO_2 emission by 0.174 to 0.358 tonne per TEU (or 45.5%–63%) against OS when it is economically feasible.

Although the economic feasibility of LN is not promising under the current situation, the environmental improvement is significant. CO_2 emissions can be reduced considerably as long as LN is economically feasible, NO_x emissions can be reduced 85%–90%, and SO_x and PM emissions can be nearly eliminated. We also observe that the just-enacted sulphur control regulation may lead to a more prevailing use of very-low sulphur fuel oil (approximately 50%–80% more expensive than 380 cst fuel oil), and the new project in Yamal region may lead to a cheaper price of LNG (or 30% lower than current level). With the joint effect of the potential increase in oil bunker price and decrease in LNG bunker price, LNG-fuelled container shipping on the NSR may—in the future—become much more economically feasible.

The contribution of this study is that we assess environmental impact based on an economic feasibility analysis of a clean energy application in Arctic shipping, because the connection has been ignored in the literature. We hope it can provide insights for further research on green shipping in this region.

Notably, this study has limitations. The main limitation is that the environmental consequences of various emissions on the Arctic or other regions are not analysed. For example, the Arctic is extremely vulnerable to black carbon. This analysis is beyond the scope of this study but will be included in our further research. In addition, we will also consider more greenhouse gases and pollutants and their impacts on the Arctic environment (especially the warming effect from black carbon), the influence of the sulphur limit regulation enacted in 2020, the development of technologies such as more new types of engines and energies, and supply chains of these energies in Arctic shipping.

References

Arpiainen, M. and Kiili, R., 2006. Arctic shuttle container link from Alaska US to Europe. *Helsinki: Aker Arctic Technology (Report k-63)*.

BLOOMBERG, 2015, Why Shippers Are Turning to LNG-Powered Vessels. Available: https://www.bloomberg.com/news/articles/2015-09-23/lng-powered-ships-gain-as-rising-output-answers-oil-price-tumult

Bouman, E.A., Lindstad, E., Rialland, A.I. and Strømman, A.H., 2017. State-of-the-art technologies, measures, and potential for reducing GHG emissions from shipping – a review. *Transportation Research Part D: Transport and Environment*, *52*, pp.408-421.

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

Cariou, P., Cheaitou, A., Faury, O. and Hamdan. S., 2019. The feasibility of Arctic container shipping: the economic and environmental impacts of ice thickness. *Maritime Economics & Logistics*, published: 05 December 2019.

Dalsøren, S.B., Samset, B.H., Myhre, G., Corbett, J.J., Minjares, R., Lack, D. and Fuglestvedt, J.S., 2013. Environmental impacts of shipping in 2030 with a particular focus on the Arctic region. *Atmospheric Chemistry & Physics Discussions*, *13*(4), pp. 1941–1955.

Ding, W., Wang, Y., Dai, L. and Hu, H., 2020. Does a carbon tax affect the feasibility of Arctic shipping?. *Transportation Research Part D: Transport and Environment*, *80*, 102257 (available online 08 February 2020).

DNV GL, 2015. In Focus-LNG as Ship Fuel. *Latest developments and projects in the LNG industry. DNV GL Maritime, Høvik.*

DNV GL, 2018. Assessment of selected alternative fuels and technologies. *DNV GL—Maritime*.

Erikstad, S.O. and Ehlers, S., 2012. Decision support framework for exploiting Northern Sea Route transport opportunities. *Ship Technology Research*, *59*(2), pp.34-42.

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.

Furuichi, M. and Otsuka, N., 2014. Economic Feasibility of Container, Finished Vehicle and LNG Transport by Arctic Shipping. In *PIANC World Congress, San Francisco, CA, June* (pp. 1-5).

Gulf-times, 2018, Novatek reduces cost estimate for second Arctic LNG facility. Available: https://www.gulf-times.com/story/589897/Novatek-reduces-cost-estimate-for-second-Arctic-LN

IMO report, 2016, Studies on the feasibility and use of LNG as a fuel for shipping.

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.

Levander, O., 2011. Dual fuel engines latest developments. *Director*, *Concept design*, *MLS. Hamburg: Wärtsilä*.

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

Lindstad, E. and Rialland, A., 2020. LNG and cruise ships, an easy way to fulfil regulations—Versus the need for reducing GHG emissions. *Sustainability*, 12(5), 2080.

Liu, M. and Kronbak, J., 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*(3), pp.434-444.

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

Moe, A., 2014. The northern sea route: smooth sailing ahead? *Strategic Analysis*, *38*(6), pp.784-802.

Omre, A., 2012. *An economic transport system of the next generation integrating the northern and southern passages* (Master's thesis, Institutt for marin teknikk).

Otsuka, N., Izumiyama, K. and Furuichi, M., 2013. Study on feasibility of the Northern Sea Route from recent voyages. In *Proceedings of the International Conference on Port and Ocean Engineering Under Arctic Conditions*.

Paxian, A., Eyring, V., Beer, W., Sausen, R. and Wright, C., 2010. Present-day and future global bottom-up ship emission inventories including polar routes. *Environmental science & technology*, *44*(4), pp.1333-1339.

Peters, G.P., Nilssen, T.B., Lindholt, L., Eide, M.S., Glomsrød, S., Eide, L.I. and Fuglestvedt, J.S., 2011. Future emissions from shipping and petroleum activities in the Arctic. *Atmospheric Chemistry and Physics*, *11*(11), p.5305.

Psaraftis, H.N. and Kontovas, C.A., 2013. Speed models for energy-efficient maritime transportation: a taxonomy and survey. *Transportation Research Part C: Emerging Technologies*, 26, pp.331-351.

Raza, Z., 2014. The commercial potential for LNG shipping between Europe and Asia via the Northern Sea Route. *Journal of Maritime Research*, *11*(2), pp.67-79.

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.

Theocharis, D., Rodrigues, V.S., Pettit, S. and Haider, J., 2019. Feasibility of the Northern Sea Route: The role of distance, fuel prices, ice breaking fees and ship size for the product tanker market. *Transportation Research Part E: Logistics and Transportation Review*, 129, pp.111-135.

Tran, N.K. and Haasis, H.D., 2015. An empirical study of fleet expansion and growth of ship size in container liner shipping. *International Journal of Production Economics*, *159*, pp.241-253.

Verny, J. and Grigentin, C., 2009. Container shipping on the northern sea route. *International Journal of Production Economics*, *122*(1), pp.107-117.

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), pp. 11-13.

Winther, M., Christensen, J.H., Plejdrup, M.S., Ravn, E.S., Eriksson, Ó.F. and Kristensen, H.O., 2014. Emission inventories for ships in the arctic based on satellite sampled AIS data. *Atmospheric Environment*, *91*, pp.1-14.

Xu, H., Yin, Z., Jia, D., Jin, F. and Ouyang, H., 2011. The potential seasonal alternative of Asia–Europe container service via Northern sea route under the Arctic sea ice retreat. *Maritime Policy & Management*, *38*(5), pp.541-560.

Xu, H., Yang, D. and Weng, J., 2018. Economic feasibility of an NSR/SCR-combined container service on the Asia-Europe lane: a new approach dynamically considering sea ice extent. *Maritime Policy & Management*, *45*(4), pp.514-529.

Yoo, S.-I., 2019. Global Status and Outlook of LNG Fuelled Ship & LNG Bunkering. *International LNG Fuelled Ship & Bunkering Conference 2019.* Available at: http://www.mof.go.kr/jfile/readDownloadFile.do?fileId=MOF_ARTICLE_28194&fileSeq=2.

Yumashev, D., van Hussen, K., Gille, J. and Whiteman, G., 2017. Towards a balanced view of Arctic shipping: estimating economic impacts of emissions from increased traffic on the Northern Sea Route. *Climatic Change*, 143, 143-155.

Zhang, Y., Meng, Q. and Ng, S.H., 2016. Shipping efficiency comparison between Northern Sea Route and the conventional Asia-Europe shipping route via Suez Canal. *Journal of Transport Geography*, *57*, pp.241-249.

Zhang, Y., Meng, Q. and Zhang, L., 2016. Is the Northern Sea Route attractive to shipping companies? Some insights from recent ship traffic data. *Marine Policy*, 73, pp. 53-60.

Zhao, H., Hu, H. and Lin, Y., 2016. Study on China-EU container shipping network in the context of Northern Sea Route. *Journal of Transport Geography*, *53*, pp.50-60.

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