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# Development potential of the Northeast Passage based on a multinomial-logit-based stochastic user equilibrium model

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**Abstract** We developed a multinomial-logit-based stochastic user equilibrium (MNL SUE) model incorporating time value of cargo to investigate future proportions of cargo flow through the Northeast Passage (NEP) and the Suez Canal Route between representative ports. We studied navigation during the ice-free and ice-covered seasons using sea ice projections for 2070 based on 1991–2021 NEP ice data. Sailing distance and time between selected ports are lower via the NEP than the Suez Canal Route. Under the scenario of year-round operation of the NEP, the proportion of cargo flow through the NEP is estimated to be 68.5%, which represents considerable commercial potential. Proportions are higher for the ice-free season and for ports at high latitudes. We also assessed flow under different scenarios. Under the scenario of fuel price increase, proportion of flow through the NEP in the ice-covered season is expected to increase. If time value is ignored, flow through the NEP is expected to increase all year round. If shippers become more cost-conscious, flow through the NEP is also expected to increase.

**Keywords** **Northeast Passage, multinomial-logit-based stochastic user equilibrium (MNL SUE), time value, scenario analysis**

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## 1 Introduction

The Northeast Passage (NEP) is attracting increasing attention because of the melting of sea ice and the lengthening of the navigation season caused by global warming. The shortest sea route between Northeast Asia and Northwest Europe is currently the route via the NEP; it is 40% shorter than the conventional Suez Canal Route (SCR) (Cai et al., 2020). Reduction in shipping distance can reduce both sailing time and cost. Between 2013 and 2020, China Ocean Shipping Company (COSCO) undertook 42 voyages. The use of the NEP reduced travel time and fuel consumption by 508.5 d and 14550 t respectively; this proves the huge economic potential of the NEP. There is a thriving shipping industry between Northeast Asia and Northwest Europe. In 2020, the volume of maritime trade between these two regions was USD 18.83 billion or 40.38% of the total maritime trade between Asia and Europe. The conventional SCR is currently the primary shipping route between Northeast Asia and Northwest Europe; congestion and slowdown in some sections are common because of the rapid expansion of maritime trade. According to some experts, the size of the global maritime transport industry could increase by 2.4–12 times by the middle of the 21st century (Sardain et al., 2019); this highlights the importance of the development of Arctic shipping routes. In this study, our primary goal is to investigate the possible development of the NEP to support future commerce.

Lengthening of the summer ice-free season creates opportunities for the commercial operation of the NEP.

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There have been suggestions that the Arctic shipping routes could become navigable much earlier than previously predicted in models (Cao et al., 2022) and that the NEP could be open year-round by 2050 (Liu, 2015). The NEP has attracted widespread attention because of its economic potential. Zhang et al. (2009) posited that replacing the traditional shipping route by an Arctic route could result in annual cost savings of 53.3–127.4 billion USD. Li and Li (2014) argued that an Arctic route can shorten the length of the shipping cycle and gradually shift the center of cargo flow toward the periphery of the Arctic route. Xia and Hu (2017) compared the shipping profit indices of the conventional and Arctic routes and concluded that the Arctic route had geographical advantages. Zhang (2016) created a container profit estimation model and a tanker cost model, compared the transport efficiencies of the NEP and SCR, and concluded that the NEP presents economic benefits only for small and medium-sized tanker operators. Pruyn (2016) examined shipping cost and time under four scenarios and argued that the NEP is unlikely to replace the conventional SCR. Sailing distance, time, and cost are lower via the Arctic than the conventional route. Wang and Zhang (2017) used a negative exponential network flow allocation approach to examine the development potential of the NEP and other routes. Wang et al. (2017) highlighted the commercial value of Arctic routes; they integrated the time value of cargo into operating costs and concluded that the costs associated with Arctic routes are lower than those of conventional routes. However, some researchers are less confident about the navigability of Arctic routes. Zeng et al. (2020) used an interdisciplinary multinomial-logit-based (MNL) model and scenario analysis to study the Suez Canal and Arctic routes and China–Europe rail transport; they concluded that the commercial development potential of the Arctic route is limited because of disadvantages associated with the geography and location of the Arctic and the rapid development of competitors. Currently, the NEP is navigable only in summer. Ice class ships remain idle during winter and generate maintenance costs. Liu and Kronbak (2010) calculated the operating costs of a non-ice class ship using the SCR all year round and those of an ice class ship that uses the NEP in summer and SCR during the rest the year; they concluded that the operating mode of the ice class ship is economically unviable. Liu et al. (2021) calculated operating costs for four scenarios; these include single and double fleets using the NEP and SCR during different seasons. They concluded that the likelihood of business-as-usual operating modes is higher than that of NEP modes for container transit over the longer term.

Most studies have focused on cost comparisons and traditional costing models and have based their analyses on current sea ice conditions in the NEP. Few studies have used multidisciplinary models or have examined future scenarios of the Arctic sea ice cover or the future navigability of the NEP. Therefore, in this study, we integrated time value of cargo and sea ice projections for 2070 to investigate the future navigability of the NEP. We used transportation models to examine the development potential of the NEP for future commercial operation.

# 2 Current navigation status and sea ice trends

## 2.1 Navigation status

The foundations for the future commercial development of NEP were laid in 2009 by the first international commercial transit and in 2018 by the first container transit. Since then, bulk and general cargo have been the most common cargo types; bulk carriers, tankers, and general cargo ships have been the most common vessels transiting the NEP; vessels of most flag states use Russian facilities and the number of cargo transits from Russia is the highest.

### 2.1.1 Annual freight volume and growth rate

The total annual freight volume (sum of transit voyages and voyages within Russia) of the NEP has increased considerably between 2012 and 2021. In 2021, it was $3.485 \times 10^{-7}$ t, which is 350% of the mean of the five previous years. The volume of freight transported within Russia has grown quickly and has resulted in the rapid increase in the freight volume of the NEP. Figure 1 shows the total amount of freight transported through the NEP from 2012 to 2021 and its growth rate.

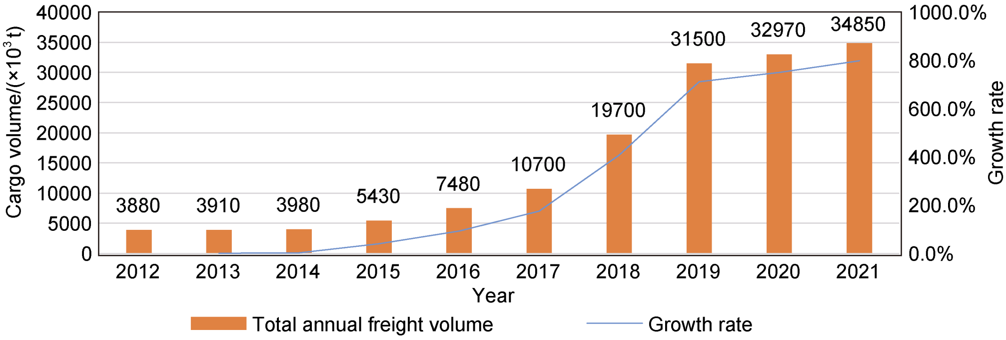

**Figure 1** Total annual freight volume through the Northeast Passage and its growth rate for 2012–2021. Data source: Northern Sea Route Information Office (NSRIO) (https://arctic-lio.com/).

### 2.1.2 Seasonal distribution of voyages

Because of the seasonality of Arctic sea ice there is a clear seasonal distribution in the number of voyages. Navigability is high between July and October; the number of voyages during this period accounts for 58.4% of all voyages between 2016 and 2021. September has the best conditions for shipping; the number of voyages in September accounts for up to 17.9% of all voyages (Figure 2).

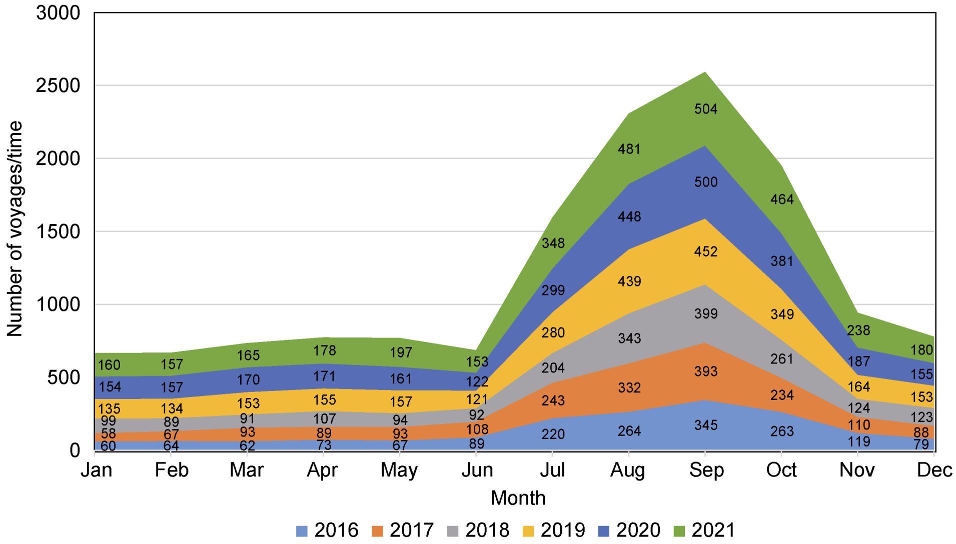

**Figure 2** Seasonal distribution of the number of voyages through the Northeast Passage for 2016–2021. Data source: Northern Sea Route Information Office (NSRIO) (https://arctic-lio.com/).

### 2.1.3 Vessel types

More than 20 types of vessels have sailed through the NEP. Between 2011 and 2021, the most common vessel type was general cargo ships; they made 150 voyages, which represent 30.80% of the total number of voyages. Tankers and bulk carriers were the second and third most common vessels and were responsible for 18.13% and 13.96% of the total number of voyages, respectively (Figure 3).

## 2.2 Sea ice trends

Sea ice is the most important environmental factor affecting ship navigation. It has notable impacts on vessel speed and safety. The Arctic has been warming rapidly in recent decades and sea ice extent has declined significantly. Data released by the Copernicus Marine Environment Monitoring Service (CMEMS) for 1991–2021 show negative interannual trends in sea ice thickness and concentration in the NEP as well as notable seasonal trends. In 1991, average sea ice thickness and concentration in the NEP were 1.18 m and 73.6%, respectively; in 2021, they were 0.81 m and 59.14%, respectively. This represents decreases of 31.4% in thickness and 19.6% in concentration over 31 years. Sea ice thickness and concentration in the NEP reached a record high in 1998 and have declined ever since. After 2002, thickness dropped to below 1 m and reached a record low in 2007.

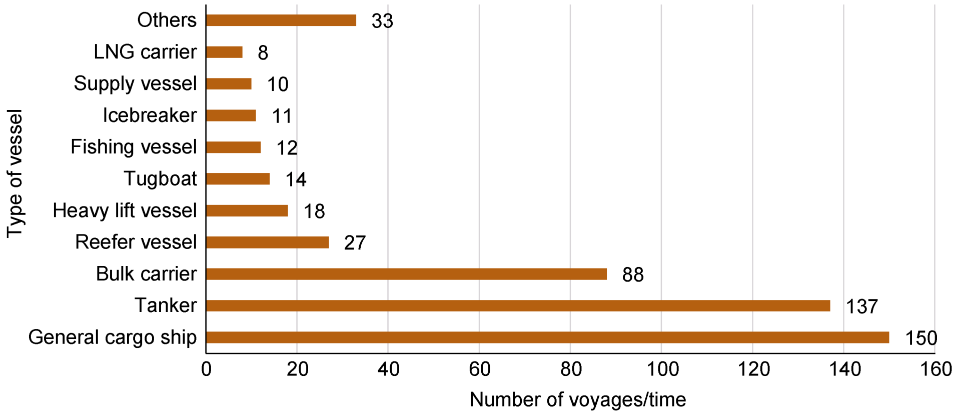

**Figure 3** Different vessel types and the number of voyages through the Northeast Passage for 2012–2021. Data source: Northern Sea Route Information Office (NSRIO) (https://arctic-lio.com/).

There are large monthly variations in the sea ice distribution in the NEP. We calculated monthly average sea ice thickness and concentration from CMEMS data for 1991–2021. Between July and November, average monthly sea ice thickness and concentration were 0.37 m and 36.7%, respectively; between January and June, they were 1.21 m and 88.1%, respectively. September had the best sea ice conditions for navigation; ice thickness and concentration were 0.18 m and 15.3%, respectively (Figures 4a and 4b).

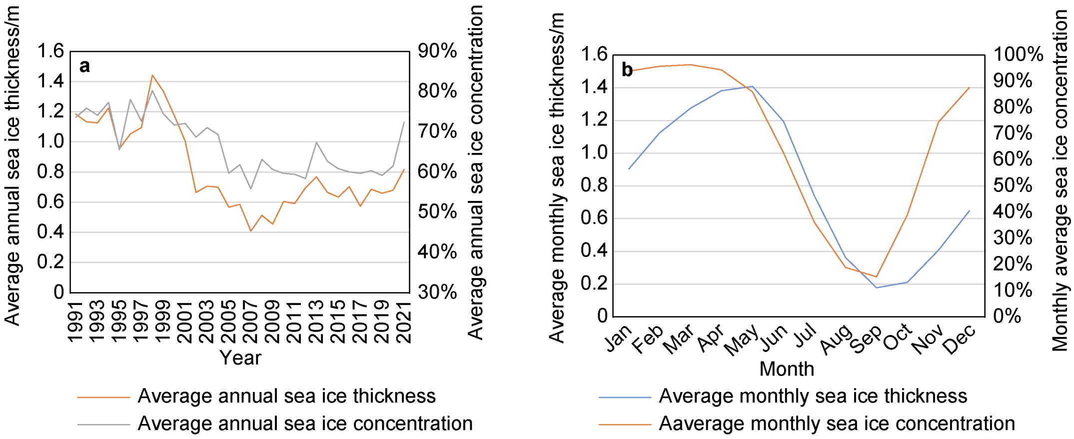

**Figure 4** Average annual (**a**), monthly (**b**) sea ice thickness and concentration in the Northeast Passage for 1991–2021. Data source: European Copernicus Marine Environment Monitoring Service (https://marine.copernicus.eu/).

# 3 Model description and assumptions

## 3.1 Model description

To forecast the share of the NEP in the maritime transport market, we determined the likelihood that shippers will choose the NEP in the future. In this study, we extended the regular functionalities of a multinomial-logit-based stochastic user equilibrium (MNL SUE) model.

### 3.1.1 Principles

In the transportation industry, the stochastic user equilibrium (SUE) model is the most frequently used approach for route selection between given endpoints. In cases with multiple route possibilities between the same endpoints, the model assumes that travelers would choose the route with the lowest perceived travel cost. It assumes that travelers can only have a rough perception of the travel cost, which can differ from the actual cost. The probability that a route is chosen is the probability that the route has the lowest perceived travel cost, but routes with higher costs may also be chosen because of random factors. The independence of irrelevant alternatives (IIA) of the MNL SUE model is satisfied when the alternative routes are independent of one another. The MNL SUE model is widely used because of its simple structure and ease of interpretation. The main advantage of the MNL SUE model is that it provides a closed-form logit probability expression; as a result, precise computation of results is possible and IIA is satisfied (Ling, 2017). The basic form of the model is as follows:

$$P_r = \frac{\exp\{-\theta \times C_r\}}{\sum_{r=1}^{n} \exp\{-\theta \times C_r\}}, (r = 1,2,3...,n) \tag{1}$$

$$P_r \in [0,1], \tag{2}$$

$$\sum_{r=1}^{n} P_r = 1, \tag{3}$$

where $r$ represents one of the routes between the endpoints; $n$ is the number of routes between the endpoints; $P_r$ is the probability that route $r$ is chosen; $C_r$ is the perceived travel cost of route $r$; $\theta$ is the dispersion coefficient which reflects the degree of travelers' perception of route $r$ and is inversely proportional to the perception error.

### 3.1.2 Modifications

The commercial development potential of the NEP is increasing because of global warming and the accelerated melting of Arctic sea ice. In this study, we determined the freight share of the NEP and SCR under future sea ice conditions. Because of the high efficiency and cargo value of container shipments, the number of shipments has increased considerably in recent decades and maritime transport efficiency has become an important focus. To select the best maritime route, shipping companies must take into account shipping time and cost. Therefore, we modified the model to (1) include a generalized cost function that integrates transport time and cost, and (2) use a relative value instead of the absolute cost; this is because absolute shipping costs are very large and minor differences between routes would result in very large differences in absolute costs.

The NEP and SCR offer very different transport environments. The NEP is partially covered by ice and the entire SCR is in open water. As a result, IIA is satisfied. The final goal function for the probability of choosing a certain route is obtained as follows:

$$P_r = \frac{\exp\left\{-\theta \times \left[\left(C_r + V_r\right)/\left(C+V\right)_{\min}\right]\right\}}{\sum_{r=1}^{n}\exp\left\{-\theta \times \left[\left(C_r + V_r\right)/\left(C+V\right)_{\min}\right]\right\}}, (r = 1, 2, 3..., n) \quad (4)$$

where $V_r$ is the time value of cargo and $(C+V)_{\min}$ is the minimum total route cost between the given endpoints.

Our modifications are based on those of Wang and Zhang (2019), but there are some differences. In this study, future sea ice conditions were used as the basis of our analysis and cargo value per unit weight of container cargo was used to determine cargo time value.

### 3.1.3 Parameters

The dispersion coefficient $\theta$ is a dimensionless parameter that measures the discrepancy between perceived and actual travel costs. It reflects travelers' familiarity with the transportation system. A large $\theta$ value is associated with a small perception error; as a result, more travelers will choose the path with the lowest cost (Zhou, 2015). In a large number of cases, a $\theta$ value of 2 results in a good match between model results and actual allocation. Therefore, we set the $\theta$ value of the base model to 2 and tested other θ values in the scenario analysis (Section 5.3).

The time value $V$ of container shipment mainly comes from the value of the capital occupation of the cargo (Zhang, 2011). It is the interest on the working capital and is the product of average container cargo value, interest rate, and total shipping time. The average unit cargo value of container shipment in the first 9 months of 2021 was 4.71 USD·kg$^{-1}$ and the interest rate was 4.35% with reference to the base rate for short-term corporate working capital loans.

## 3.2 Assumptions

Maritime developments and Arctic sea ice conditions result in different economic benefits. Economic benefits vary according to port location and ship type, size, and ice class. In this section, we present the assumptions that were incorporated into our model.

### 3.2.1 Vessel type

The first container ship traveled through the NEP in 2018. It was operated by the Danish shipping giant Maersk and marked the beginning of container ship transits through the Arctic Ocean. In this study, we focused on container ships because of the immense commercial potential of container shipping in general and for the NEP in particular.

### 3.2.2 Ice class

Changes in ice conditions are expected to improve the navigability of ordinary ships. By 2070, ordinary merchant ships might be able to navigate under conditions that currently require ice class PC6 (equivalent to ARC5) (Huang et al., 2021). In this study, we focused on the year 2070. We used CMEMS sea ice data from 1991–2021 and an Autoregressive Integrated Moving Average (ARIMA) model to obtain projections of monthly sea ice thicknesses in 2070. The ARIMA model is commonly used for time series prediction. It is appropriate for our ice thickness projections because we have univariate time series data and need to take into account correlations. We used the Augmented Dickey Fuller (ADF) as a unit root test for data stationarity. Differencing was applied to the non-stationary series. An ARIMA model was built for each stationary series. Table 1 shows the projected sea ice thickness for each month in 2070.

Model residuals were entirely white noise; this indicates the absence of autocorrelation in the residuals. In the Lagrange Multiplier (LM) test of the residual terms, all $p$ values exceeded 0.05; this indicates the absence of serial correlation between residual terms. Therefore, we concluded that the performance of the model was satisfactory.

There was a negative trend in the time series data after differencing. As a result, long-term forecasts based on these data contained negative values. However, sea ice thickness cannot be negative. Therefore, negative projected sea ice thickness values in June to November were set to 0 m. We considered this period as the ice-free season during which ordinary ships can sail freely. December to May was considered as the ice-covered season with first-year ice of low and medium thicknesses. Data from COSCO show that Ice1 class ice-resistant ships are the ship type that is the most commonly used for the NEP. Ice1 class ships can sail independently during the ice-free season and can benefit from the pilotage services of icebreakers during the ice-covered season. They are the focus of our study.

**Table 1** Projected monthly sea ice thickness in the Northeast Passage in 2070

| Month | Jan | Feb | Mar | Apr | May | Jun |
|---|---|---|---|---|---|---|
| Sea ice thickness/m | 0.532 | 0.775 | 0.646 | 0.801 | 0.604 | 0 |
| Month | Jul | Aug | Sep | Oct | Nov | Dec |
| Sea ice thickness/m | 0 | 0 | 0 | 0 | 0 | 0.909 |

### 3.2.3 Vessel size

Container ship size is limited by the effect of low temperatures on ship steel toughness and maximum icebreaker width. The largest container ship that can travel through the Arctic route is a medium-sized ship of about 50000 t with a container capacity of about 4500 TEU. Table 2 shows the parameters of the *OOCL Texas*, which is a container ship of Orient Overseas Container Line Ltd. (OOCL).

**Table 2** Parameters of the container ship *OOCL Texas*

| Volume | Building cost | Ship size | Dead weight tonnage | Gross tonnage | Net tonnage | Horse power |
|---|---|---|---|---|---|---|
| 4578 TEU | $5.0\times10^7$ USD | 260 m × 32.2 m | 50610 t | 40168 t | 22450 t | 36560 kW |

Ships that sail through the Arctic sea ice area need to be reinforced using thicker and stronger steel plates. As a result, building costs and tonnage for Ice1 class ships are 10% higher than those of standard container ships (Luo et al., 2019; Feng, 2020). The *OOCL Texas* weighed about 44185 t and cost about $5.5 \times 10^7$ USD after being strengthened and becoming an Ice1 class vessel.

### 3.2.4 Ports of origin, destination, and shipping routes

The NEP is the shortest maritime route connecting Northeast Asia and Northwest Europe. Its commercial operation will have effects on these two regions. In this study, we focused on large ports in countries that are involved in trading between Northwest Europe and Northeast Asia. We took into consideration geographical location and container throughput of ports and focused our study on four major ports in Northeast Asia—Shanghai, Busan, Yokohama, and Vladivostok—and four major ports in Northwest Europe—Hamburg, Rotterdam, Oslo, and Antwerp. The SCR is currently the primary cargo shipping route between Northeast Asia and Northwest Europe. Therefore, in this study, we examined the direct port-to-port transportation between Northeast Asia and Northwest Europe via the NEP and SCR.

We considered the NEP as $r = 1$ and SCR as $r = 2$. The probability that the NEP is chosen between two given ports is $P_1$. The probability that SCR is chosen is $P_2$. We examined 16 origin–destination pairs. Each pair has the same denominator values in Equation 4.

## 4 Cargo flow through the NEP and SCR

### 4.1 Calculation of shipping time

### 4.1.1 Shipping distance

Table 3 shows distances between ports for different shipping routes; distances were calculated using Free Map Tools.

**Table 3** Distance between ports via the NEP and SCR (unit: n mile)

| | Hamburg | | Rotterdam | | Oslo | | Antwerp | |
|---|---|---|---|---|---|---|---|---|
| | NEP | SCR | NEP | SCR | NEP | SCR | NEP | SCR |
| Shanghai | 7941 | 10729 | 7868 | 10608 | 7703 | 11114 | 7950 | 10593 |
| Busan | 7445 | 11048 | 7392 | 10917 | 7227 | 11423 | 7473 | 10902 |
| Yokohama | 7171 | 11431 | 7082 | 11317 | 6918 | 11823 | 7164 | 11302 |
| Vladivostok | 6962 | 11541 | 7010 | 11435 | 6846 | 11942 | 7092 | 11420 |

### 4.1.2 Single voyage time

We set ship speed in open water to 18 kn because ship navigation data indicate it as the optimal speed for 5000-ton container ships in terms of cost and fuel economy. It takes about 16 h to pass through the Suez Canal where there is a speed limit of 7–8 kn. For the NEP, there are ice-free and ice-covered waters; in the ice-covered area, there are independent and assisted navigation areas. We set assisted navigation speed in the ice-covered area to 4 kn because the speed of the Russian nuclear-powered icebreaker is typically 3–5 kn (Jiang and Hu, 2021). The speed of independent navigation was assumed to increase with the Ice Numeral (*IN*). Following the Arctic Ice Regime Shipping System (AIRSS) implemented by Transport Canada, *IN* was derived as follows:

$$IN = IM_{\text{ice}} \times C_{\text{ice}} + IM_{\text{ow}} \times C_{\text{ow}} , \tag{5}$$

where $IM_{\text{ice}}$ is the ice multiplier, which measures the severity of each type of sea ice for a specific ship and lies between −4 and 2; $C_{\text{ice}}$ is the concentration of each sea ice type and is between 0 and 10; $IM_{\text{ow}}$ is the ice multiplier for a specific ship type in open water and is equal to $(10- C_{\text{ice}})$; $C_{\text{ow}}$ represents sea ice concentration in open water. Large $IM_{\text{ice}}$ is associated with good navigation conditions. Positive *IN* indicates that independent navigation is possible. Negative *IN* indicates that ice breaking pilotage services are necessary. Independent navigation speed *S* in ice-covered area was derived as follows (McCallum, 1996):

$$S=0.0027\times IN^3-0.0398\times IN^2+0.2489\times IN+3.8385, \tag{6}$$

According to Equation 5, Ice1 class ships require ice-breaking services during the ice-covered season. Experience of Chinese merchant ships indicates that ice-breaking services are typically needed for 2–3 sections in the NEP. Therefore, we set the number of sections requiring ice-breaking services to 2. Table 4 shows sailing times between ports for different routes during the ice-free and ice-covered seasons.

### 4.2 Cost accounting

International shipping cost *C* is the sum of capital costs, operating costs, and voyage costs (Xu et al., 2011).

### 4.2.1 Capital costs

The depreciation cost of the ship makes up the

**Table 4** Sailing time between ports via different routes (unit: d)

| | Hamburg | | | Rotterdam | | | Oslo | | | Antwerp | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | NIF | NIC | SCR | NIF | NIC | SCR | NIF | NIC | SCR | NIF | NIC | SCR |
| Shanghai | 18.4 | 25.4 | 25.3 | 18.2 | 25.2 | 25.0 | 17.8 | 24.8 | 26.2 | 18.4 | 25.4 | 24.9 |
| Busan | 17.2 | 24.2 | 26.0 | 17.1 | 24.1 | 25.7 | 16.7 | 23.7 | 26.9 | 17.3 | 24.3 | 25.7 |
| Yokohama | 16.6 | 23.6 | 26.9 | 16.4 | 23.4 | 26.6 | 16.0 | 23.0 | 27.8 | 16.6 | 23.6 | 26.6 |
| Vladivostok | 16.0 | 23.0 | 27.1 | 16.2 | 23.2 | 26.9 | 15.8 | 22.9 | 28.1 | 16.4 | 23.4 | 26.9 |

Notes: NIF indicates Northeast Passage sailing time in ice-free season; NIC indicates Northeast Passage sailing time in ice-covered season; SCR indicates traditional Suez Canal Route passage sailing time.

majority of the capital cost. We used the composite life method to calculate depreciation cost as follows:

Annual depreciation = (original ship value − estimated net salvage value)/ estimated useful life, (7)

The capital cost of the ship was set annually. Depreciation was lower for shorter voyages. An ordinary ship has a depreciable life of 25 years, whereas ice-class ships have a depreciable life of 20 years because ice-class ships travel for extended periods of time in cold climates. We set ship scrap price to 500 USD·t$^{-1}$.

### 4.2.2 Operating costs

Crew wages, insurance, maintenance expenses, and overheads are the key components of the operating costs.

#### 4.2.2.1 Crew wages

A medium-sized container ship needs about 20 crew members. Total monthly wages are about 100000 USD (Li et al., 2015). Crew wages for Arctic shipping are typically 20% higher than those for the traditional route because of the harsh conditions and the requirements of superior sailing skills and extensive sailing experience.

#### 4.2.2.2 Insurance premiums

A basic marine premium and an extra premium make up the annual premiums for marine vessels. Typically, the marine premium is 2% of the construction cost of the ship. For SCR, there is an additional pirate insurance, which is 0.16% of the construction cost. For the Arctic route, there is an additional environmental insurance, which is 0.08% of the construction cost.

#### 4.2.2.3 Maintenance expenses

Annual maintenance cost is a proportion of the ship's value. For example, for a container ship that is similar to the *OOCL Texas*, annual maintenance cost is roughly 3‰ of the ship's value. Ships sailing in Arctic waters suffer more damage and wastage because of low temperature and the large amounts of floating ice. Therefore, we set the maintenance cost to 6‰ per year for a container ship that is similar to the *OOCL Texas* and that sails through the NEP.

#### 4.2.2.4 Overheads

By convention, ship overheads were set to 50% of crew wages.

### 4.2.3 Voyage costs

Voyage costs include fuel costs, material costs, canal dues, and tariffs for ice-breaking services.

#### 4.2.3.1 Fuel costs

Daily fuel consumption during the voyage was calculated as follows:

$$Q=k\times S^3\ , \tag{8}$$

where $Q$ represents the daily fuel consumption of the ship (unit: t·d$^{-1}$); $S$ represents the speed (unit: kn); $k$ is the ship function coefficient, which is influenced by the engine power of the ship (Xie, 2009). The main engine power of the *OOCL Texas* is 36560 kW. As a result, $k$ was set to 0.0181 (Notteboom and Vernimmen, 2009). The price of IF0380 fuel oil was set to 350 USD·t$^{-1}$.

#### 4.2.3.2 Material costs

Material costs were set to 15% of fuel costs.

#### 4.2.3.3 Canal dues

We calculated Suez Canal dues for a single voyage on the basis of the net tonnage of ships and the canal rate schedule (Table 5) as follows:

$$f_s = scnt \times r \times SDR\ , \tag{9}$$

where $scnt$ is the net tonnage of ships traveling through the Suez Canal, $r$ is the Suez Canal rate, and $SDR$ is the Special Drawing Rights to US dollar conversion factor. The cost of one single voyage through the Suez Canal was computed using a 14-ton weight assumption for each container.

#### 4.2.3.4 Tariffs for ice-breaking services

According to the Northern Sea Route Administration of Russia, tariffs for ice-breaking services vary according to ship type and size, ice conditions, zones, and the number of zones in which ice-breaking services are needed.

**Table 5** Suez Canal dues for container ships (unit: USD)

| Vessel type | SC Net tonnage | | | | | | | | SDR/SCNT | |
|---|---|---|---|---|---|---|---|---|---|---|
| | First 5000 | | Next 5000 | | Next 10000 | | Next 20000 | | Next 30000 | |
| Container ships | Laden | Ballast | Laden | Ballast | Laden | Ballast | Laden | Ballast | Laden | Ballast |
| | 8.35 | 7.1 | 5.73 | 4.88 | 4.45 | 3.78 | 3.12 | 2.65 | 2.89 | 2.46 |

### 4.3 Total costs

Table 6 shows total costs between ports for different routes; costs were determined by integrating time value and shipping cost over ice-free and ice-covered seasons.

### 4.4 Allocation for the NEP and SCR

We used the MNL SUE model to compute flow allocation on the basis of total route cost. The proportions of cargo flow for different routes in the ice-free and ice-covered seasons are shown in Table 7 and Table 8, respectively.

Tables 7 and 8 show that the proportion of flow through the NEP is larger than that through the conventional SCR. A large proportion indicates high navigation potential. Average year-round proportion is 68.5% and 31.5% for the NEP and SCR, respectively. The route through the NEP is shorter than that through the SCR; the NEP is associated with lower voyage costs and shorter sailing time. A shorter sailing time also improves capital and vessel turnover and increases the time value of cargo.

Proportions of flow vary with port location. Proportion of flow through the NEP increases with port latitude and is considerably higher for Oslo than for Antwerp, Rotterdam, or Hamburg in Northwest Europe. Proportion of flow through the NEP is the highest between Vladivostok and Oslo and the average is 75.0% throughout the year. For Northeast Asia, Vladivostok, which is in the Russian Far East, has obvious geographical advantages and has the highest cost-saving potential. Our results show that the allocation and navigation potential of the NEP increase with port latitude and proximity to the NEP.

**Table 6** Total transportation cost between ports via different routes (unit: ×$10^4$ USD)

| | Hamburg | | | Rotterdam | | | Oslo | | | Antwerp | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | NIF | NIC | SCR | NIF | NIC | SCR | NIF | NIC | SCR | NIF | NIC | SCR |
| Shanghai | 171 | 225 | 244 | 170 | 223 | 241 | 166 | 220 | 252 | 171 | 225 | 241 |
| Busan | 160 | 214 | 250 | 159 | 213 | 248 | 156 | 210 | 258 | 161 | 215 | 247 |
| Yokohama | 155 | 208 | 258 | 153 | 207 | 256 | 149 | 203 | 267 | 154 | 208 | 256 |
| Vladivostok | 149 | 203 | 261 | 151 | 205 | 259 | 148 | 201 | 269 | 153 | 207 | 258 |

Notes: NIF indicates route costs of Northeast Passage in ice-free season, NIC indicates route costs of Northeast Passage in ice-covered season, SCR indicates route costs of the Suez Canal Route.

**Table 7** Proportions of cargo flow between ports for different routes in the ice-free season

| | Hamburg | | Rotterdam | | Oslo | | Antwerp | |
|---|---|---|---|---|---|---|---|---|
| | NEP | SCR | NEP | SCR | NEP | SCR | NEP | SCR |
| Shanghai | 69.98% | 30.02% | 69.90% | 30.10% | 73.73% | 26.27% | 69.20% | 30.80% |
| Busan | 75.39% | 24.61% | 75.16% | 24.84% | 78.84% | 21.16% | 74.45% | 25.55% |
| Yokohama | 79.30% | 20.70% | 79.47% | 20.53% | 82.86% | 17.14% | 78.77% | 21.23% |
| Vladivostok | 81.62% | 18.38% | 80.55% | 19.45% | 83.86% | 16.14% | 79.86% | 20.14% |

**Table 8** Proportions of cargo flow between ports for different routes in the ice-covered season

| | Hamburg | | Rotterdam | | Oslo | | Antwerp | |
|---|---|---|---|---|---|---|---|---|
| | NEP | SCR | NEP | SCR | NEP | SCR | NEP | SCR |
| Shanghai | 54.12% | 45.88% | 53.93% | 46.07% | 57.18% | 42.82% | 53.44% | 46.56% |
| Busan | 58.32% | 41.68% | 57.99% | 42.01% | 61.38% | 38.62% | 57.46% | 42.54% |
| Yokohama | 61.76% | 38.24% | 61.75% | 38.25% | 65.19% | 34.81% | 61.18% | 38.82% |
| Vladivostok | 63.78% | 36.22% | 62.77% | 37.23% | 66.20% | 33.80% | 62.19% | 37.81% |

Proportions of flow also vary with season. Average proportion of flow through the NEP is 77.1% in the ice-free season and 59.95% in the ice-covered season. Proportion is higher in the ice-free than in the ice-covered season and the difference is 17.2%. This is because ships can travel at higher speeds in the ice-free season. As a result, sailing time is reduced and the time value of cargo is increased. During the ice-free season, ice-breaking services are unnecessary and voyage costs decrease. Therefore, the navigation potential and allocation of the NEP increase as navigation conditions improve.

## 5 Scenario analysis

Shipping companies choose routes on the basis of a number of factors; these include shipping costs, cargo timeliness, channel amenities, hinterland ports and box sources along the route, and the political climate of neighboring nations. The probability that a route will be chosen increases with lower shipping costs, shorter shipping time, more developed infrastructure along the route, presence of hinterland ports, abundant box sources, and politically stable neighboring nations. Among these factors, shipping cost and time have considerable impacts on route choice. Model parameter values also impact flow allocation. Fuel cost accounts for a sizeable proportion of navigation costs. Therefore, we analyzed the development potential of the NEP under alternative scenarios to take into account the uncertainties associated with future shipping developments. Scenario analysis has been widely used to forecast future project developments. We conducted three simulations to examine the effects of fuel price increase and variations in time value and perception error in terms of travel cost.

### 5.1 Fuel price increase

International environmental concerns and the development of new energy technologies may lead to future fuel restrictions or increased fuel prices or emission taxes. These actions could result in considerable increases in fuel cost. Because fuel cost accounts for more than 50% of shipping costs, fluctuations in fuel prices may affect route selection. We examined a future scenario in which bunker fuel price doubles and is 700 USD·t$^{-1}$. Figure 6 shows changes in market share for the NEP and SCR under this scenario. If fuel price increases, the proportion of flow through the NEP increases by 4.97% in the ice-covered season and decreases by 0.99% in the ice-free season. This indicates that more shippers will choose the NEP over the SCR in the ice-covered season. In the ice-free season, sailing speed is higher, fuel consumption and shipping costs increase, and the probability that shippers choose the NEP decreases.

### 5.2 Zero time value

Ocean transportation has taken over as the primary form of transportation in international trade because of the high volume and competitive freight rates that are involved. However, the ocean shipment cycle is long and efficiency is low. We examined the future scenario in which shippers only consider shipping costs and time value is considered as zero. Figure 7 shows changes in market share for the NEP and SCR under this scenario. With zero time value, the proportion of flow through the NEP increases by an average of 3.16% in the ice-covered season and reaches 63.1%; it increases by 1.11% in the ice-free season and reaches 78.2%. Transit through the NEP takes more time in the ice-covered than in the ice-free season. With zero time value, the magnitude of cost reduction is larger in the

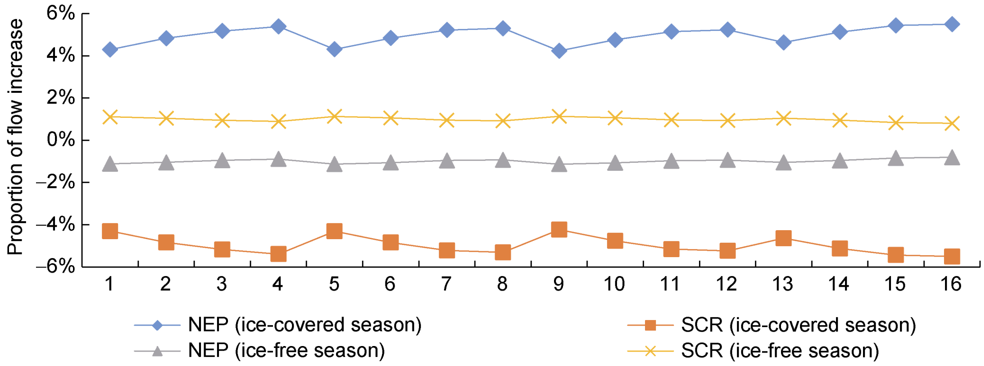

**Figure 6** Changes in market share for different routes under the scenario of fuel price increase. 1: Shanghai (S) to Hamburg (H), 2: Busan (B) to H, 3: Yokohama (Y) to H, 4: Vladivostok (V) to H, 5: S to Rotterdam (R), 6: B–R, 7: Y–R, 8: V–R, 9: S to Antwerp (A), 10: B–A, 11: Y–A, 12: V–A, 13: S to Oslo (O), 14: B–O, 15: Y–O, 16: V–O.

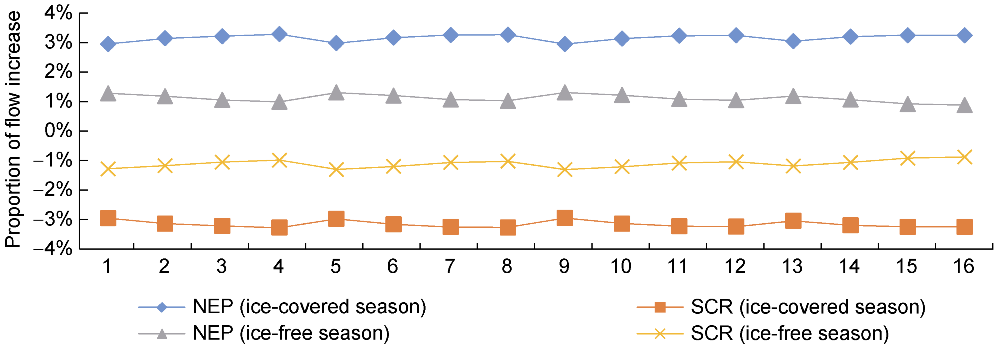

**Figure 7** Changes in market share for different routes under the scenario of zero time value.

ice-covered than in the ice-free season. As a result, the increase in the proportion of flow through the NEP is higher in the ice-covered than in the ice-free season under this scenario.

### 5.3 Different values of the dispersion coefficient $\theta$

The dispersion coefficient reflects travelers' sensitivity to their trip expense estimates. A high value of $\theta$ indicates that most travelers would choose the route with the lowest cost. A low value of $\theta$ indicates that some travelers would choose routes with higher costs. Perception errors influence route selection. We examined scenarios with $\theta$ values of 0.5, 2, and 3 (Figure 8). A $\theta$ value of 0.5 is associated with large perception error. In this case, travelers' knowledge of route cost is low and the proportion of travelers choosing the SCR, which has a high cost, increases noticeably. Proportion of flow through the SCR is 47.5% in the ice-covered season and 42.4% in the ice-free season. Proportion of flow through the SCR increases by 7.4% and 19.5% in the ice-covered and the ice-free season, respectively. A $\theta$ value of 3 is associated with a lower perception error. Average proportion of flow through the NEP is 64.5% in the ice-covered season and 85.7% in the ice-free season. It is higher than that for a $\theta$ value of 2 and the difference is 4.6% and 8.6% in the ice-covered and the ice-free season, respectively. This indicates that if shippers are more aware of route cost, more of them will select the NEP, which is less expensive than SCR.

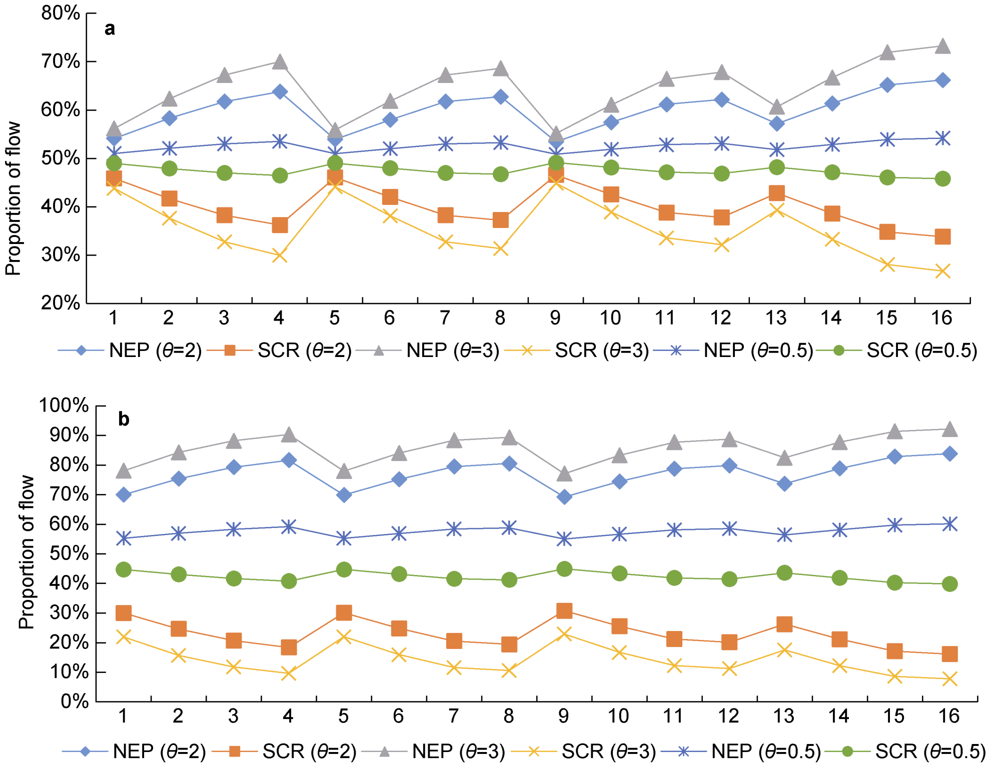

**Figure 8** Proportions of flow for different routes in the ice-covered season (**a**), the ice-free season (**b**) for different values of the dispersion coefficient $\theta$.

## 6 Conclusions

We examined the proportions of cargo flow through the NEP and SCR under future scenarios of regular year-round operation of the NEP. Proportion of flow through the NEP is higher than that through SCR; it reaches 68.5% for different ports because of reductions in shipping cost and time and indicates considerable development potential. Both season and port location impact the market share of the NEP in the marine trade between Northeast Asia and Northwest Europe. There is more traffic through the NEP in the ice-free season because of higher sailing speeds and absence of ice-breaking costs. Proportion of flow through the NEP increases with port latitude and proximity to the NEP. Under the scenario of fuel price increase, proportion of flow through the NEP increases in the ice-covered season and decreases slightly in the ice-free season. In the scenario of zero time value, we assumed route selection is determined by shipping costs only and time value is ignored. Under this scenario, proportion of flow through the NEP increases in both ice-free and ice-covered seasons. The probability of the NEP being chosen by shippers as their preferred route increases with shippers' sensitivity to cost. Overall, the NEP has tremendous development potential. It will capture a large share of the shipping market between Northeast Asia and Northwest Europe if it opens fully for commercial operation.

Compared with the countries in the Arctic, China has a geographical disadvantage. In terms of scientific research in the Arctic, the United States and European industrialized nations remain the leaders and China still lags behind. To prepare for the future commercial operation of Arctic shipping routes, China needs to conduct more scientific research, especially on Arctic sea ice. We also need to conduct trial commercial voyages through the Arctic using more vessel and cargo types to increase our Arctic navigation experience. China needs to increase our collaboration with Arctic nations and take active roles in the planning and construction of infrastructure for Arctic shipping routes. By establishing a global communication platform, we may also participate in the management and development of Arctic routes.

**Declaration of competing interest** The authors declare no conflict of interest.

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