Trade Volume Prediction Based on a Three-Stage Model When Arctic Sea Routes Open

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Abstract: With the advancement of global warming, the Arctic sea routes (ASRs) may open for the entire year. The ASRs will be far more competitive than they are now, and they will be the major international sea routes in the future. To date, most studies have researched the economic feasibility in the short term from a company’s perspective. To help to plan the shipping market in the future, we developed a three-stage model to simulate the trade demand of the ASRs for the long term. This model firstly considers the seasonal sea ice dynamics in the future and plans new paths for vessels shipping through the Arctic. Additionally, an improved trade prediction model was developed to adapt to the long-term forecasts. After verification, the accuracy of the model was found to be very high ($R^2 = 0.937$). In comparison with another transportation cost model and a trade prediction model, our model was more reasonable. This study simulated the trade volumes of China, Europe (EU), and North America (NA) in 2100 with the ASRs open. The results show that the percentage of port trade can be up to 26% in representative concentration pathway (RCP)2.6, and the percentage of port trade can be up to 52% in RCP8.5.

Keywords: Arctic; route planning; Arctic sea route; trade forecast

1. Introduction

The Arctic sea routes (ASRs) are maritime passages connecting the Pacific and Atlantic oceans. The ASRs include the following three routes: the Northeast Passage (NEP), the Northwest Passage (NWP), and the Transpolar Sea Route (TSR). The NEP is a maritime passage situated along the Russian Arctic coastline. The NWP is a maritime passage situated along the Canadian and Alaskan Arctic coastline. The TSR is a maritime passage across the center of the Arctic Ocean. The ASRs attract many exploratory transit voyages and studies on navigation feasibility with Arctic sea ice shrinking [1–8]. An ASR can reduce the distance, times, and shipping costs among Asia, Europe, and North America. For example, the NEP can reduce the transport distance between East Asia and Europe by 25% compared to the Suez sea route [9]. The NWP can reduce the transport distance between East Asia and Europe by 25% compared to the Suez sea route [9]. The NWP can reduce the distance from Shanghai in China to Saint John in Canada by approximately 3500 nm compared to the Panama sea route [10,11].

With the increase in the possibility of the ASRs opening [12,13] and due to their economic benefits, Russia explored much of the ASRs in the 1980s [3]. Ships that can transport in ice regions were built, and short-haul sea lines linking Europe and the Russian Arctic coastline were developed. Since then, the number of exploratory transit voyages has increased [3,14]. The studies on economic feasibility have also increased since the sea ice extent declined greatly. According to a literature survey, most studies consider that the ASRs will not be economically competitive [3,4,14–16]. The methods of these studies...
assumed that the size \[11,14,15,17\] of the ships travelling via the ASRs is smaller than those using the traditional sea routes (e.g., Suez and Panama canals), that the shipping demand of the ASRs is far lower than the traditional sea routes, and that the ASR paths are the same as the current paths in the Arctic. These assumptions are reasonable for short-term simulations but not for long-term simulations.

In the long term, the Arctic will have no ice in summer \[18,19\]. Ice-free summers are projected to occur even if the total warming since pre-industrial times is below 2 °C \[20\], but not necessarily with 1.5 °C of warming \[21\]. According to the latest model inter-comparison (Coupled Model Inter-Comparison Project Phase 6, CMIP6), ice-free summers are projected to occur by 2050 \[22\]. The sea routes will be completely different from the current paths of the ASR. The size of ships passing through will not be limited by the shallow strait. Additionally, ships will pass more often on the high seas in the Arctic. This will reduce shipping costs and improve the economic competitiveness of the ASRs greatly. Since the opening window ASRs will increase significantly till 2100 and transportation costs will decline greatly, the shipping demand for the ASRs will increase in the long term. Thus far, no studies have assessed the economic feasibility in the long term. This is important for port construction and shipping development, which require 50~100 years of planning \[23\].

The methods of shipping or trade volume forecast mainly include trend extrapolation and causal models, as the development of trade or the economy is changeable. Methods of trend extrapolation based on historical scenes face difficulties in predicting conditions in the long term. Causal models are usually applied for forecasting long-term conditions. However, unlike climate forecasts, there are very few forecasts in the transportation field. Recently, there have been a few studies focused on forecasting the shipping or trade volume of the ASRs in the long term \[24,25\]. Causal models (i.e., a system dynamics model and econometrics) are used to forecast the shipping volume in the long term \[25,26\]. A system dynamics model can increase the understanding of cause-and-effect interaction. However, in order to examine the interaction of variables (e.g., capacity of ice-class vessel and sea ice conditions), a variable-controlling needs to be set. This may lead to underestimating the shipping volume. This study selected the econometrics gravity model to predict the long-term trade volume of the ASRs, which has been successfully applied for shipping forecasts in global scale \[26\].

This study aimed to develop a three-stage simulation model to predict how many ports and trades would select the ASRs by which to transport in the long term. The simulation of this study firstly considered the Arctic seasonal paths, which is close to reality. Furthermore, we improved the trade prediction model to adapt to long-term forecasts. The model was applied for the year 2100 under the lowest emission pathway (representative concentration pathway (RCP2.6) and the highest emission pathway (RCP8.5). The results of this study provide the new paths of the ASR. Additionally, we analyzed the trade demand from China to Europe and North America.

2. Materials and Methods

2.1. Data

This study included transit cost data and trade simulation data. The transit cost data included (i) ship data, (ii) sea ice thickness, (iii) shipping costs, (iv) ice class vessel cost, and (v) shipping speed. The trade simulation data included (i) port data, (ii) distance of sea line, (iii) gross domestic product (GDP), and (iv) social and historical data.

2.1.1. Ship Data

In the future, vessels of a larger ice class may ship across the Arctic, and the vessel size will not be limited by shallow water. Therefore, we assume that vessels of a larger ice class are built to ship cargo. The parameters of ice class ships were estimated based on those of an ordinary ship. We selected a bulk carrier for the simulations. A container ship was not included because it was reported that liner shipping is not likely to be used in the Arctic \[27\]. A tanker was also not included in this study because the shipping marker of
tankers depends on the distribution of resources. This study aims to provide support for a wider scope of shipping origin–destination (OD) matrices.

A 70,000-Deadweight tonnage (DWT) bulker, which has an average ship size according to the Maritime Transport Report 2018, was selected in this study. The ship information of the bulk carrier is shown in Table 1.

Table 1. Size and parameters of the bulk carrier in this study.

|               | Load Displacement/t | Gross Tonnage (GT)/t | Main Engine Horsepower (M/E HP) | Deadweight Tonnage (DWT) | Building Cost/Tens of Thousands of USD | Net Tons (NT)/t | Service Years |
|---------------|---------------------|----------------------|---------------------------------|--------------------------|----------------------------------------|----------------|--------------|
| Bulk carrier  | 85,846              | 356,222              | 11,791.2                        | 70,000                   | 3500                                   | 20,900         | 10           |

1 Maritime Transport Report 2018. 2 MarineTraffic (https://www.marinetraffic.com (accessed on 6 April 2019). 3 Scheepvaartwest (https://www.scheepvaartwest.be (accessed on 6 April 2019). 4 Shipping online tool (http://tool.sol.com.cn (accessed on 6 April 2019). 5 Maritime Sales (https://www.maritimesales.com (accessed on 6 April 2019).

Shipping through the Arctic requires ships to have an anti-ice ability. This study evaluates the prospects of Polar Class 6 (PC6) and open-water (OW) ships.

2.1.2. Shipping Cost

The study measured shipping costs with cost per TEU. The shipping costs include capital, operating, fuel, and transit fees.

Capital cost is represented by the building cost in this study (Table 1). The operating cost includes crew, insurance, and repair and maintenance (R&M) costs. Insurance includes hull and machinery (H&M) and protection and indemnity (P&I) costs. The operating costs were obtained from a survey of the literature and websites [5,15,28–31]. The crew cost of the bulk carrier is about USD 3505 per day (source: http://www.sol.com.cn/ (accessed on 6 April 2019)). The R&M cost was calculated based on the building cost, which is USD 875,000 per year. The insurance cost is usually around 0.45–0.7% of the capital cost. The H&M cost of the bulk carrier is about 0.55% of capital cost. The P&I cost is about USD 630 USD per day [32].

Transit fees denote the charge when ships pass a canal or a sea route. According to the official price of the Suez Canal, the Suez Canal charges a transit fee based on the type of vessel, the navigation direction, the Suez Canal Net Tonnage (SCNT), and whether the vessel is loaded or ballasted, and it also depends on the Special Drawing Right (SDR) rate. This study calculates the transit fee for the Suez Canal, assuming that the ship is loaded.

According to the official pricing of the Panama Canal, the Panama Canal charges fees according to ship type, cargo type, ballast, or cargo. This study calculates the transit fee for the Panama Canal based on a Panamax locks ship type, assuming that the ship is loaded.

The Russian NSR Administration charges an ice-breaking fee based on the size and ice class of the ship and the number of sea areas the ship travels through. According to the Canadian Coast Guard, the ice-breaking fee is charged based on the number of voyages.

2.1.3. Ice Class Vessel Cost

The ice class vessels’ (OW and PC6) cost includes the capital cost, operating cost (including crew, insurance, repair and maintenance (R&M), and fuel costs). The cost of OW and PC6 was obtained from a literature survey. We selected seven papers [3,15,17,27,29,30,33], the shipping costs of which were generally applied in other studies on the economic feasibility of ASRs. The average crew cost and insurance cost included in the seven papers were applied in this study. The capital cost, R&M, and engine horsepower of the OW and PC6 vessels were sourced from J.L. Liu (2015) [32], which investigated the capital cost and engine horsepower of different ice class ships from ice class shipyards. The engine horsepower was used to calculate the fuel cost. Compared with the cost of ordinary ships, the increasing percentage of ice class vessel cost was list in Table 2. The final costs of the different ship types are shown in Table A1 in Appendix A.
Table 2. The parameters of ice class vessel costs in this study.

|                  | OW    | PC6   |
|------------------|-------|-------|
| Capital cost     | 20%   | 30%   |
| Insurance        | 50%   | 50%   |
| Crew cost        | 10%   | 10%   |
| R&M              | 20%   | 30%   |
| Engine horsepower| 0%    | 30.80%|

2.1.4. Sea Ice Thickness (SIT) Data

To simulate the sea routes in the year 2100, sea ice data for 2100 should be predicted. The Coupled Model Intercomparison Project Phase 5 (CMIP5) provided many models to simulate sea ice thickness (SIT) in the future under various representative concentration pathway (RCP) scenarios. In this study, we selected multiple models to eliminate the dispersion of different models (Table 3). The average of the models was applied in the route planning of this study. The models were selected following the method of Melia et al. (2016) [18] on ASR planning. In order to eliminate the bias of each model, these model outputs were corrected with the Pan-Arctic Ice Ocean Modeling and Assimilation System (PIOMAS). The models selected in this study are shown in Table 3. Additionally, we selected the highest emission pathway (RCP8.5) and the lowest emission pathway (RCP2.6) to simulate the routes. The seasonal average sea ice thickness distributions under RCP2.6 and RCP8.5 are shown in Figure 1. The seasonal shipping paths were planned based on the sea ice thickness.

Table 3. General circulation models (GCMs).

| Institution                                      | GCM Model                                                                 |
|-------------------------------------------------|---------------------------------------------------------------------------|
| Met Office Hadley Centre                        | Hadley Centre Global Environment Model version 2-Earth System: HadGEM2-ES |
| National Center for Atmospheric Research         | Community Climate System Model, version 4: CCSM4                           |
| National Center for Atmospheric Research         | Community Earth System Model, Community Atmosphere Model, version 5: CESM1-CAM5 |
| Model for Interdisciplinary Research on Climate (MIROC) | MIROC version 5: MIROC5                                                   |
| Max Planck Institute for Meteorology (MPI)      | MPI Earth System Model, low resolution: MPI-ESM-LR                       |
| Applied Physics Laboratory (University of Seattle) | Pan-Arctic Ice Ocean Modeling and Assimilation System: PIOMAS            |

2.1.5. Speed Data

We built a speed model for the PC6 and OW ships based on real shipping data of the Arctic. The real shipping data were obtained from the website (http://www.shipxy.com/ (accessed on 6 April 2019)) and Melia et al. (2016). The model is shown in Figure 2. The speed of the ordinary ship was 20 knots, based on Lasserre (2014). The speed was used to calculate the fuel cost and the shipping time.

2.1.6. Trade Simulation Data

Trade simulation data were the variables of the gravity model; this included trade data as the dependent variable and GDP, population data, common official language, common border, common colonial history, and regional trade agreement data as the independent variables.
Figure 1. The sea ice thickness (SIT) distribution of the open-water (OW) and Polar Class 6 (PC6) vessels on the Arctic sea route (ASR) for each month in the year 2100 (the red line is the boundary of the PC6 vessel’s shipping scope; the green line is the boundary of the OW vessel’s shipping scope; according to the Canadian Coast Guard, the safe navigation region of the PC6 ship is the sea with below 1.2 m SIT, and the safe navigation region of the OW ship is the sea with below 0.15 m SIT).

Figure 2. The speed model of the OW and PC6 vessels (the speed was 16 knots when the PC6 and OW ships passed through open water).

The trade data between countries from 2008 to 2017 were obtained from the database of the United Nations Conference on Trade and Development (https://www.unctad.org/ (accessed on 6 April 2019)).

The GDP and population data included historical (data for 2008–2017) and prediction data (data for 2100), which were obtained from the World Bank Databank (http://databank.worldbank.org/) and the International Institute for Applied Systems Analysis (IIASA) Shared Socioeconomic Pathways (SSP) database (https://tntcat.iiasa.ac.at/SspDb/ (accessed on 6 April 2019)), respectively. The forecasted GDP and population data were simulated based on different shared socioeconomic pathways. In this paper, we selected the SSP5 data (“fossil-fueled development”) to ensure variable data consistency because only SSP5 can provide the gas emissions of both representative (greenhouse gas) concentration pathways (RCPs)—RCP8.5 and RCP2.6.
The common official language, common border, common colonial history, and regional trade agreement data were collected from the CEPII research center’s GeoDist and Gravity datasets (http://www.cepii.fr/CEPII/en/bdd_modele/bdd_modele.asp (accessed on 6 April 2019)).

The trade of the country was assigned to ports based on the throughput of ports. The port data and the throughput data in this study were obtained from the shipping statistics website IHS Markit (https://www.ihsmarkit.com/ (accessed on 6 April 2019)).

The distances of traditional sea routes were calculated via Searoutes (https://www.searoutes.com/ (accessed on 6 April 2019)). The website generates sea lines based on real ship trajectories, which made it possible to calculate the sea line length from port to port.

2.2. Model

The forecast of trade via the ASRs in the long term was based on the cost between two ports and the throughput of ports. The cost of new paths in the Arctic needed to be calculated. Therefore, a transport cost model with path planning was built in this study. The port-to-port trade scale will change with the cost of trade declining when the ASRs open. Thus, a trade forecast model considering transit cost is developed in this study. To evaluate trade in the ASRs, a trade design based on shipping costs is applied in this study. Thus, according to the above considerations, we developed a three-stage model that adapts to long-term trade simulations. The three-stage model integrates transport cost calculation, trade forecast, and trade assignment. The transport cost calculation is based on ArcPy and NetworkX2.5. The trade forecast and trade assignment are calculated with Python 3.7.

The work flow of the model is shown in Figure 3.

![Figure 3. The work flow of the three-stage model.](image)

2.2.1. An Improved Trade Forecast Model (RAUGII)

The gravity model is based on causality, which is suitable for long-term simulations. This model has successfully been applied to a long-term shipping traffic forecast [26] recently. The theory of this model is that trade is proportional to the size of the economy and the distance of trade, broadly speaking. The model can be described as follows:

\[ F_{ij} = \frac{M_i \cdot M_j}{d_{ij}} \]  

(1)

where \( F_{ij} \) is the trade flow from the origin (O) \( i \) to the destination (D) \( j \); \( M_i \) is the size of the economy of the origin \( i \); \( M_j \) is the size of the economy of the destination \( j \); \( d_{ij} \) is the distance from the origin \( i \) to the destination \( j \).
However, when the model was applied on a large scale, the distance of trade was usually represented by the geographic straight-line distance of O–D. This is not suitable for the simulation of trade when the ASRs open because the simulation trade will not change with the geographic straight-line distance of O–D when the ASRs open. Furthermore, the model cannot take all factors into account. A residual term is usually used to represent these unknown factors. This study uses a gravity model with a residual term to simulate the long-term trade volume. The gravity model (unconstrained gravity, UG) can be described as follows:

$$\log(\text{Trd}) = \beta_1 \cdot \log(\text{GDP}_i) + \beta_2 \cdot \log(\text{GDP}_j) + \beta_3 \cdot \log(\text{POP}_i) + \beta_4 \cdot \log(\text{POP}_j) + \beta_5 \cdot \log(D_{ij}) + \beta_6 \cdot \text{contig} + \beta_7 \cdot \text{colony} + \beta_8 \cdot \text{comlang_ethno} + \beta_9 \cdot \text{comcol} + \beta_{10} \cdot \text{comlang_off} + RA + \epsilon$$

(2)

where Trd is the trade flow from country i to country j; GDP and POP are the GDP and population of a country, respectively; $D_{ij}$ is the annual average cost of ports from country i to country j; contig indicates whether the country i and j share a border; colony indicates whether the country i and j have a colonial relationship; comlang_ethno indicates whether the ethnic language of countries i and j is the same; comcol indicates whether the countries i and j belong to the same colony. Additionally, comlang_off indicates whether the official language of countries i and j is the same; RA is the residual term; $\beta$s are the estimated parameters. The $\epsilon$ is the random error term.

Recently, the residual adjustment method named unconstrained gravity with residual adjustment (RAUG) was used to improve the accuracy of the model in the study of Sardain et al. (2019) [26]. They consider that the predicted value is proportional to the true value. This is to say that the unconsidered factors in the model increase with the trade increasing.

In our opinion, Sardain’s assumption is not reasonable, as the factors related to economic scale can be represented by the GDP completely. The unconsidered factors are static, i.e., they do not change over time. Based on this assumption, we developed a new residual adjustment model (RAUGII), in which residual adjustment is shown as the following:

$$RA' = T_0 - T_1$$

(3)

where RA' is the residual adjustment; $T_0$ is the average of historical trade data; $T_1$ is the average of predicated trade before the residual adjustment. The final predicted trade ($Trd'$) is as follows:

$$Trd' = RA' + \hat{T}$$

(4)

where $\hat{T}$ is the predicated trade before the residual adjustment.

2.2.2. Transport Cost Model

The transport cost model considers the path dynamics of the ASRs. With the distribution of sea ice varying, the shipping path and the cost per length will change. The monthly cost of using the ASRs was the cheapest of the costs of the PC6 and OW vessels.

The transport cost includes capital, operating, fuel, and transit fees. It varies with sailing speed ($v$) and time ($T$). The sailing speed ($v$) in the Arctic is a function of sea ice thickness, shown in Figure 2.

$$\text{Cost} = \left(\frac{ZC}{Y \cdot 365} + CC + IC + MC \cdot T + FP \cdot FC + a \cdot TF\right) / Cap$$

(5)

$$T = \sum_{l=1}^{L} \frac{l_i}{v}$$

(6)

where Cost is the shipping cost of one voyage per ton of cargo; ZC is the capital cost of one ship; CC is the crew cost per day; IC is the insurance cost per day; MC is the R&M cost per day; FC is the fuel consumption per voyage; FP is the fuel price, set as USD 600 per ton; $Y$ is the service years of the ship; $a$ is a binary number, representing whether the ship was
charged a transit fee; $TF$ is the transit fee; $Cap$ is the tons of cargo loaded on the ship; $l_i$ is the unit length of the path; $v$ is the speed passing through the length. The upper limit $L$ is the path from origin to destination.

Fuel consumption ($FC$) was calculated based on the rate of fuel consumption ($RFC$). $FC$ and $RFC$ were calculated with Equations (3) and (4), respectively.

$$FC = \sum_i l_i V \cdot RFC$$ \hspace{1cm} (7)

$$RFC = \frac{\nabla \cdot V^3}{P}$$ \hspace{1cm} (8)

where $FC$ is the fuel consumption of a path that consists of the fuel consumption of pixels in the path; $RFC$ is fuel consumption per time unit; $\nabla$ is the load displacement; $P$ is the engine horsepower; $l_i$ is the unit length of the path; and the upper limit $L$ is the path from origin to destination.

The cost of using the ASRs was calculated using a minimum cost function, which was calculated as follows:

$$Cost = \text{Min}(FP \cdot FC + \sum_i \left( \left( \frac{ZC}{365 \cdot CC + IC + MC} \right) \cdot l_i \cdot v \cdot \frac{24}{24} + TF \right) / Cap)$$ \hspace{1cm} (9)

The cost of using the ASRs is partly illustrated in Table 2.

### 2.2.3. Trade Assignation Model

The country-to-country trade volume was assigned port-to-port via OD port weights using the following assignment formula:

$$Tr_{p1p2} = \frac{W_{P1}}{W_{C1}} \cdot \frac{W_{P2}}{W_{C2}} \cdot Tr_{C1C2}$$ \hspace{1cm} (10)

where $Tr_{p1p2}$ is the trade flow between Port 1 and Port 2; $W_{P1}$ and $W_{P2}$ are the throughputs of Port 1 and Port 2, respectively; $W_{C1}$ and $W_{C2}$ are the throughputs of Country 1 and Country 2, respectively; $Tr_{C1C2}$ is the trade flow between Country 1 and Country 2.

This study involves many ports and routes, and the capacity of the ports is difficult to calculate. Therefore, this study adopted an unconstrained assignation model. We allocated trade to routes based on the cost of shipping. The formula is as follows:

$$f_{l_{ij}} = \frac{\text{EXP}(-\theta \cdot C_{l_{ij}})}{\sum_a \text{EXP}(-\theta \cdot C_{a_{ij}}) \cdot Tr_{d_{ij}}}$$ \hspace{1cm} (11)

where $f_{l_{ij}}$ is the trade flow of path $k$ between ports $i$ and $j$; $Tr_{d_{ij}}$ is the trade flow between ports $i$ and $j$; $C_{l_{ij}}$ is the cost of the path $k$ between ports $i$ and $j$; $\sum_a \text{EXP}(-\theta \cdot C_{a_{ij}})$ is the sum of costs of all paths between ports $i$ and $j$; $\theta$ is the estimated parameters. The trade percentage of the ASRs is shown in Table 2.

### 3. Results

#### 3.1. The Planning Sea Routes

We used the cheapest cost path of the OW and PC6 vessels to represent the cost of using the ASRs in one month. For example, we selected the OW to ship in the month if both the OW and the PC6 can ship in the month and the shipping cost of OW is cheaper than that of PC6. We select the PC6 to ship in the month when the OW can’t ship via ASRs in the month. Figure 4 shows the minimum monthly path cost of the ASRs in 2100. Each path line represent the cheapest path in a month from the source point to the end points.
red paths are the simulation results of RCP2.6. The blue paths are the simulation results of RCP8.5. In the RCP2.6 scenario, the ASRs are open for PC6 for about 7 months. We used the paths of the PC6 vessel to represent the paths of the ASR. All paths from the Bering Strait to the Norwegian Sea are close to the coast of Russia. The shipping time for the PC6 vessel in summer from Rotterdam to Yokohama is about 17.9 days. From the Bering Strait to Baffin Bay, the paths mainly pass via Viscount Melville Sound. The shipping time for the PC6 vessel in summer from New York to Yokohama is about 18.5 days. In the RCP8.5 scenario, the ASRs are open for the PC6 vessel all year round, and for the OW vessel from July to December. The costs of the OW vessel are cheaper than those of the PC6 ship from July to December. We selected the OW vessel to ship cargo via ASRs from July to December. We used the PC6 vessel to ship cargo in other months. Most paths from the Bering Strait to the Norwegian Sea pass through the TSR. The shipping time for the OW vessel in summer from Rotterdam to Yokohama is about 17.5 days. The path from the Bering Strait to Baffin Bay mainly passes via the strait further north. The shipping time for the OW vessel in summer from New York to Yokohama is about 20.7 days. From Figure 4, we can see that the ships passing through the Arctic no longer pass through the shallow strait, even in RCP2.6. More paths in the RCP8.5 scenario pass through the TSR. This would lead to shorter shipping times and cheaper shipping costs.

Figure 4. The minimum cost path from the Bering Strait to Baffin Bay and the Norwegian Sea in different months. Under RCP2.6, paths from Source to End 2 are paths of the PC6 vessel from July to January. Paths from Source to End 1 are paths of PC6 from July to December. In RCP8.5, paths from Source to End 2 are paths of the OW vessel from August to October and paths of PC6 in other months. Paths from Source to End 1 are paths of PC6 all year round.

3.2. Trade Demand When ASRs Open among China, Europe (EU), and North America (NA)

We analyzed the trade via ASRs from China to Europe (EU) and North America (NA) under RCP2.6 (Figure 5) and RCP8.5. The trade was calculated for 12 months of the year. We found that trade via ASRs from Europe to the west coast of NA was the most frequent. The most common trade path of the ASRs from EU to the west coast of NA is the NEP or TSR. The most common trade path of the ASRs from China to the east coast of NA is the NWP. The most common trade path of the ASRs from China to EU is the NEP or TSR. As the port is located to the north, a higher trade percentage was shipped through the ASRs.

In RCP2.6, about 11–17% of the trade via ports in China occurred using ASRs for transport. About 1–10% of the trade via ports in EU occurred using ASRs for transport. About 10–14% of the trade via ports on the east coast of NA occurred using ASRs for transport. About 10–26% of the trade via ports on the west coast of NA selected ASRs for transport. The highest percentage of trade via ports along the ASRs could be up to 26%.
In RCP8.5, the trade percentage via ports along ASRs increased twice compared to that in RCP2.6 (Figure 6). About 23–36% of trade via ports in China occurred along ASRs. Approximately 2–21% of the trade via ports in EU used ASRs for transport. About 22–27% of the trade via ports on the east coast of NA occurred along ASRs. About 31–52% of the trade via ports on the west coast of NA occurred along ASRs. The highest percentage of trade via ports shipped via the ASRs could be up to 52%.

Figure 5. Percentage of trade via ports along ASRs among China, Europe (EU), and North America (NA) under RCP2.6.

Figure 6. Percentage of trade via ports along ASRs among China, Europe (EU), and North America (NA) under RCP8.5.
4. Discussion

4.1. The Planning Paths of ASR

Thus far, to verify the rationality of the model, we compared the shipping routes of the OW and PC6 vessels via ASRs in our simulation (Min_cost) with the simulation results of Melia et al. (2016) [18] at the end of the 21st century. At the same time, we compared the paths of the ASR based on the minimum shipping time model (Min_time) with the results of Melia et al. (2016) [18] (Figure 7). The simulation of Melia et al. (2016) [18] also used the shortest shipping time to plan routes. Their simulation selected five general circulation models (GCMs). Each GCM contains three ensemble members in its simulation. Their simulation offered all possible results for each GCM at the end of the 21st century. In Melia’s [18] simulations, the following results were noted:

![Figure 7. Paths of PC6 and OW ships in August crossing the Arctic based on Min_cost and Min_time models.](image)

In RCP2.6:
- The paths of PC6 from the Bering Strait to Europe in RCP2.6 were mostly via the TSR;
- The paths of PC6 from the Bering Strait to America in RCP2.6 were mostly via the following path: Bering Strait—Beaufort Sea—Viscount Melville Sound—Baffin Bay—America;

In RCP8.5:
- The paths of both OW and PC6 from the Bering Strait to Europe in RCP8.5 were mostly via the TSR;
- The paths of OW and PC6 from the Bering Strait to America in RCP8.5 were mostly the same as those in RCP2.6;
The paths of Melia et al. (2016) [18] are consistent with the paths based on the Min_time model of this study (Figure 4). The paths based on the Min_cost model of this study are roughly consistent with the results of Melia et al. (2016) [18].

4.2. Comparison of Different Transport Cost Models

To illustrate the importance of transportation cost while considering the new paths of the ASR, we compared the scope of ports via the ASRs from China to Europe based on the cost model of this study and based on a transportation cost model that takes no consideration of the new paths of the ASR. When the cost of using ASR is lower than that of the traditional sea routes, we assume that the port may select the ASR for transportation. In Figures 8 and 9, Model 1 represents the transportation cost model taking no consideration of the new paths of the ASR, and Model 2 represents the transportation cost model considering the new paths of the ASR. Both simulations of the two models are based on sea ice thickness under the same RCP scenario. In both RCP2.6 and RCP8.5, the region in EU further from the Arctic than Portugal will not transport to China via ASRs. Additionally, ports in China further from the Arctic than the Xiamen port region will rarely transport to Europe via ASR. However, in Model 2, the region farther than the north coast of France will not transport to China via ASRs in RCP 2.6. The region farther than Italy will not transport to China via ASR in RCP 8.5. Additionally, all the ports in China will transport via ASRs. This is to say that more trade demand will be placed on ASRs than expected when the ASRs open.

Figure 8. Scope of ports selecting ASRs by which to transport based on Model 1 and Model 2 in RCP2.6 (Model 1 is the transportation cost model not considering the new paths of the ASR; Model 2 is the transportation cost model considering the new paths of the ASR).

Figure 9. Scope of ports selecting ASRs by which to transport based on Model 1 and Model 2 in RCP8.5 (Model 1 is the transportation cost model not considering the new paths of the ASR; Model 2 is the transportation cost model considering the new paths of the ASR).
Besides, the origin–destination trade pairs from China to Europe via ASRs hardly change from RCP2.6 to RCP8.5 with Model 1. The origin–destination trade pairs from China to Europe via ASRs increase by 30 pairs from RCP2.6 to RCP8.5 with Model 2. This further clarifies the importance of new paths in the ASRs for economic feasibility.

4.3. Comparison of Different Gravity Models

To illustrate the rationality of the model in this paper (RAGUII), we compared the accuracy of trade between countries with the unconstrained gravity (UG) model and unconstrained gravity with residual adjustment (RAGU). The UG model has no residual adjustment. The residual adjustment of RAGU is as follows:

\[ \text{Trd}' = \frac{T_0}{T_1} \cdot \hat{T} \]  

where \( \text{Trd}' \) is the predicted trade with residual adjusting; \( T_0 \) is the average of historical trade data; \( T_1 \) is the average of predicted trade data before residual adjustment; \( \hat{T} \) is the predicted trade data before residual adjustment.

We used historical data from 2010 to 2016 to fit the model. Additionally, trade data in 2019 were utilized to validate the accuracy. By analyzing the accuracy of the three models, all of the gravity models with residual adjustment were found to show the same high accuracy. This means that the residual adjustment method can improve prediction accuracy significantly. Accuracy of the gravity models is shown in Table 4.

Table 4. Accuracy of the gravity models.

| Model   | \( R^2 \) |
|---------|-----------|
| RAUG    | 0.937     |
| RAUGII  | 0.937     |
| UG      | 0.702     |
| All of the \( p \)-values of the three models are less than 0.01. |

However, the model RAGU is based on the assumption that the residual will increase with the economy scale increasing, while the model RAGUII contradicts the assumption of RAGU. Thus, we tested the correlation between the residual of RAGU and trade volume. The Pearson correlation coefficient (R) was equal to 0.38. This means that the residual is not related to trade volume. Thus, the RAGUII model of this paper is more reasonable.

4.4. Sensitivity to Fuel Price

The cost of shipping paths is a dominant factor of trade among regions. Fuel prices are a major uncertainty of the shipping cost. We analyzed the sensitivity of fuel prices in the transportation cost via ASRs (Figure 10). We selected the shipping cost of PC6 to analyze the sensitivity of fuel prices because the PC6 vessel can ship through ASRs in both RCP2.6 and RCP8.5 scenarios. From Figure 10, we can see that the shipping cost of R1 (from the Bering Strait to the Norwegian Sea) is more sensitive to fuel prices. The increasing shipping cost rate of R1 is about 1.2 times the shipping cost of R2. Furthermore, the shipping cost in RCP8.5 is more sensitive to fuel prices than that in RCP2.6. The increasing shipping cost rate in RCP8.5 is about 1.1 times the shipping cost in RCP2.6. However, the changing percentage of shipping cost is less than 10% when fuel prices increase from USD 300 to 900 per ton.
Figure 10. The trend of shipping cost of PC6 with fuel prices increasing: (a) the changes in shipping cost under RCP2.6; (b) the changes in shipping cost under RCP8.5. R1 is the route from the Bering Strait to the Norwegian Sea. R2 is the route from the Bering Strait to Baffin Bay. The red trend line is the trend of cost of R1. The black trend line is the trend of cost of R2.

5. Conclusions

As a result of global warming, the possibility of opening the ASRs has increased, and new shipping routes will be planned to adapt to the condition of the Arctic Ocean. Thus far, there are few studies that have simulated trade through the ASRs in the long term. This study developed a three-stage model, which involves a transport cost model considering the path dynamics of the ASRs, a trade prediction model with a new residual adjustment method, and a trade assignment model.

The model was validated and compared in three stages. In the stage of planning routes in the ASRs, we compared the paths of our simulation with the results of Melia et al. (2016) [18]. Our simulation’s ASR paths are roughly consistent with the work of Melia et al. (2016) [18]. Based on the five selected GCMs, the global air surface temperature in RCP2.6 by 2100 in the multi-model means increases by 2.5 °C. The global air surface temperature for RCP8.5 by 2100 increases by 6.8 °C. In the transportation cost calculation stage, we compared the scope of ports that may select the ASRs to ship cargo based on our cost model and based on a cost model not considering the path dynamics of ASRs. The comparison shows that the ASRs may attract more ports to transport via ASRs than the simulation based on the current paths of the ASR. In the stage of trade forecast, we analyzed the accuracy of three gravity models. The models with residual adjustment show higher accuracy. Additionally, when testing the relationship of residual and trade volume, our trade prediction model is more reasonable.

By analyzing ASR paths in 2100, we could predict that shipping via ASRs will not be limited by shallow straits. Additionally, more paths pass through the TSR. By analyzing the trade among China, EU, and NA when ASRs open, we found that up to 17~36% of the trade via ports in China could be shipped via ASRs, up to 10~21% of trade via ports in EU could be shipped via ASRs, and up to 26~52% of trade via ports in NA could be shipped via ASR. The model in this study cannot take all factors into consideration, such as the delivery time, turnover rate of capital, and the development of Arctic countries. In the future, more conditions or factors should be taken into consideration in the model.

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Appendix A

Table A1. The daily costs of ice class ships and an ordinary tanker of 70,000 DWT (unit: USD/ton/day).

| Ship Type | Fuel Cost | Capital Cost | Insurance | R&M | Crew Cost | Total Cost |
|-----------|-----------|--------------|-----------|-----|-----------|------------|
| OW        | 0.11      | 0.06         | 0.03      | 0.05| 0.05      | 0.31       |
| PC6       | 0.15      | 0.07         | 0.03      | 0.05| 0.05      | 0.35       |
| Ordinary tanker | 0.11       | 0.05         | 0.02      | 0.04| 0.047     | 0.27       |

Table 2. The distances of paths and the trade percentage of ASRs between ports from China to EU and NA (partly shown).

| Country | Port | Distance in the Open Water (n mile) | Transportation Cost (USD per ton) | Trade Percentage of ASR in RCP2.6 | Trade Percentage of ASR in RCP8.5 |
|---------|------|-----------------------------------|----------------------------------|----------------------------------|----------------------------------|
| O       | D    | O                                | D                                | TSR                              | ASR                              |
| CHN     | NOR  | Dalian                           | Oslo                             | 11,444                           | 4696                             | 10.7                            | 6.0                            | 5.5                            | 51.2%                          | 51.3%                          |
| CHN     | CAN  | Dalian                           | Sydney                           | 11,199                           | 5295                             | 10.4                            | 10.1                           | 8.4                            | 50.1%                          | 50.5%                          |
| CHN     | USA  | Dalian                           | New York                         | 10,686                           | 6036                             | 10.1                            | 10.8                           | 9.0                            | 49.8%                          | 50.3%                          |
| CHN     | USA  | Dalian                           | Fall River                       | 10,750                           | 5939                             | 10.1                            | 10.7                           | 8.9                            | 49.9%                          | 50.3%                          |
| CHN     | NOR  | Tianjin                          | Oslo                             | 11,601                           | 4851                             | 10.9                            | 6.1                            | 5.7                            | 51.2%                          | 51.3%                          |
| CHN     | CAN  | Tianjin                          | Sydney                           | 11,361                           | 5450                             | 10.6                            | 10.3                           | 8.5                            | 50.1%                          | 50.5%                          |
| CHN     | USA  | Tianjin                          | New York                         | 10,848                           | 6191                             | 10.2                            | 10.9                           | 9.2                            | 49.8%                          | 50.3%                          |
| CHN     | USA  | Tianjin                          | Fall River                       | 10,912                           | 6094                             | 10.2                            | 10.9                           | 9.1                            | 49.8%                          | 50.3%                          |
| CHN     | NOR  | Shanghai                         | Oslo                             | 11,015                           | 4599                             | 10.4                            | 5.9                            | 5.5                            | 51.1%                          | 51.2%                          |
| CHN     | CAN  | Shanghai                         | Sydney                           | 11,102                           | 5198                             | 10.4                            | 10.0                           | 8.3                            | 50.1%                          | 50.5%                          |

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