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# Pendulum routes in the Northeast Passage: design and economic analysis

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**Abstract** Global warming has made the regular operation of Arctic routes possible. This study selects hub ports based on infrastructure conditions and sea ice status, and then designs two pendulum route solutions for the Northeast Passage according to the distance between hub ports and ice-covered areas. We employ an evaluation framework combining annual profit metrics with discounted net present value (NPV) analysis, conducting probabilistic economic assessments through Monte Carlo simulations (20,000 iterations). Key findings indicate that (1) both solutions demonstrate >90% probability of economic viability and (2) Solution I′, with hub ports closer to ice-covered areas than those in Solution II, yields 5.02% higher mean annual profit and 4.69% greater NPV. The results indicate that pendulum routes in the Northeast Passage can achieve economic benefits by enabling year-round regular operations. Moreover, shorter shipping distances between hub ports and ice-covered areas enhance economic viability.

**Keywords** **Northeast Passage (NEP), pendulum shipping route, shipping economy, Monte Carlo simulation**

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## 1 Introduction

The rapid melting of Arctic sea ice, driven by global warming and the “Arctic Amplification” effect, has created substantial opportunities for the development of Arctic shipping, highlighting its considerable potential (Saenko et al., 2025). Since the inauguration of Arctic routes, extensive research has been conducted to assess their economic viability in maritime transport, yielding three predominant viewpoints:

Mainstream research suggests that Arctic routes are economically viable for shipping. In comparison with traditional Suez Canal routes, Arctic routes offer shorter voyage distances (Wang and Fan, 2011), leading to reduced operational costs (Gao S L et al., 2018) and lower required freight rates (Zhang and Song, 2014), ultimately enhancing profitability. Furthermore, Arctic routes consistently demonstrate higher shipping profits than Suez Canal routes, whether or not icebreaking services are factored in (Xia and Hu, 2017).

However, some scholars argue that Arctic routes are not economically viable for shipping. Available studies suggest that Arctic routes exhibit cost disadvantages (Gao J et al., 2018; Verny and Grigentin, 2009) and profitability gaps (Liu et al., 2021) compared to traditional Suez Canal routes in container and tanker shipping. Recent research extends this finding, suggesting that such competitive disadvantages may persist until 2065 (Wu et al., 2024), while regulatory changes like the heavy fuel oil ban further exacerbate these economic challenges (Miao et al., 2025).

Finally, some scholars argue that the economic viability of Arctic routes is influenced by a range of natural and socio-economic factors (Kavirathna et al., 2023; Xu et al., 2025). Key influencing factors include icebreaking fees (Liu and Kronbak, 2010), seasonal variations and vessel types (Qian et al., 2015), ship ice-class capabilities and

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cargo utilization rates (Sibul and Jin, 2021), vessel speed (Ding et al., 2025), as well as cargo types (Zhang et al., 2025) and their time-sensitivity (Zhou et al., 2024).

While above studies primarily focused on direct shipping routes, some scholars have conducted economic analyses of transshipment (the transfer of goods between vessels during transit) models. Liu et al. (2016) pioneered a unidirectional circular route combining the Arctic route and the Suez Canal route, which was later refined by Liu et al. (2024) through vessel routing optimization modeling. Milaković et al. (2018) proposed a transshipment model using icebreaker-assisted ice-class vessels, while Jiang and Hu (2021) and Cheaitou et al. (2022) specifically designated Murmansk and Petropavlovsk ports as transshipment hubs. Building on these works, Li et al. (2024) developed a pendulum transport model that conclusively demonstrated the economic advantages of ice-class vessel operations between hub ports.

In summary, existing research on the economic viability of the Northeast Passage has primarily focused on direct shipping models. However, this approach is constrained by limited navigation windows, allowing only seasonal operation rather than year-round stable regular operation, adversely impacting shipping operations' overall economic efficiency. While some studies on transshipment models have demonstrated the potential for year-round Northeast Passage operations, they maintain that direct shipping remains more economically advantageous. Other studies have further substantiated the economic benefits of transshipment models, yet have overlooked the resource wastage associated with ice-class vessels during non-operational periods. Additionally, theoretical analyses suggest that the economic efficiency of transshipment models improves as hub ports are located closer to ice-covered areas (Shi, 2018), but this proposition lacks empirical validation. Building upon the existing literature, this study introduces the following improvements:

(1) This study designs two pendulum route solutions for the Northeast Passage to enable year-round operation of ice-class vessels while avoiding resource wastage. A comparative analysis of these solutions provides empirical validation for the theoretical relationship between hub port distance and shipping economic efficiency.

(2) Recognizing that maritime route operations constitute long-term commitments spanning multiple years, and accounting for the time value of money, this study innovatively employs net present value (NPV) as an economic evaluation metric to assess the shipping economics of Northeast Passage pendulum routes throughout the entire vessel lifecycle.

# 2 Operational status of the Northeast Passage

An analysis of the current navigational conditions of the Northeast Passage provides empirical reference data for designing the pendulum route solutions in subsequent sections.

## 2.1 Seasonal distribution of transit categories and voyage frequency in the Northeast Passage

Russian official reports classify Northeast Passage transits into two categories. The first category comprises international transits, including (1) Bilateral International Transits (BIT) between non-Russian ports, and (2) Unilateral International Transits (UIT) between Russian and non-Russian ports. The second category involves Domestic Coastal Shipping (DCS) between Russian ports. According to monitoring data from the Centre for High North Logistics, during the period 2011–2024, shipping records reveal a total of 145 bilateral international transits, 223 unilateral international transits, and 285 domestic coastal voyages, excluding 2014 due to data unavailability. Notably, bilateral international transits were the least frequent, with zero occurrences between 2022 and 2024, while unilateral international transits continued uninterrupted (Figure 1).

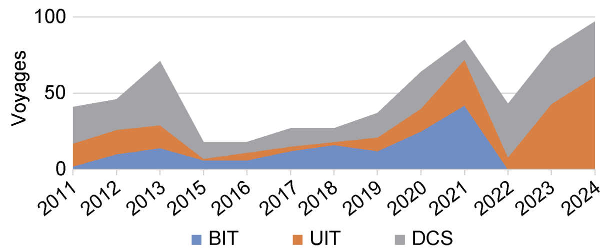



**Figure 1** The stacked area chart of transit classification in the Northeast Passage.

Due to the seasonal variability of Arctic sea ice, transit voyages through the Northeast Passage exhibit distinct seasonal patterns. During 2012–2024 (excluding 2020 due to data unavailability), July to October accounted for 92.85% of annual transit voyages, with September peaking at 36.11% (Figure 2).

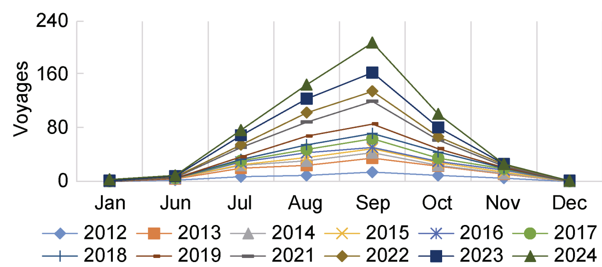



**Figure 2** Seasonal distribution of the number of voyages along the Northeast Passage.

## 2.2 Vessel types and ice class distribution of Northeast Passage transits

Statistical data from 2011 to 2024 indicate that vessel types navigating the Northeast Passage primarily included tankers, general cargo ships, bulk carriers, fishing vessels, refrigerated cargo ships, and icebreakers. Among these, tankers and general cargo ships accounted for the highest transit volumes, followed by bulk carriers, while fishing vessels, refrigerated cargo ships, and icebreakers represented smaller but notable proportions (Figure 3).

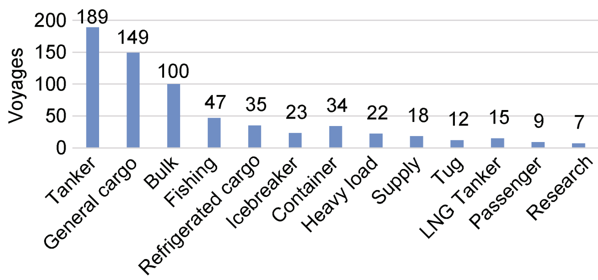



**Figure 3** Cumulative vessel types transiting the Northeast Passage, 2011–2024.

From 2012 to 2024 (excluding 2014 and 2019 due to data unavailability), vessels transiting the Northeast Passage (excluding icebreaking vessels) were primarily classified into two ice classes according to the International Association of Classification Societies (IACS) standards: non-ice class and IACS PC7. The non-ice class vessels recorded the highest transit frequency (237 voyages), followed by IACS PC7-class vessels (205 voyages). The highest ice-class vessels observed, IACS PC3, accounted for only 28 transits (Figure 4).

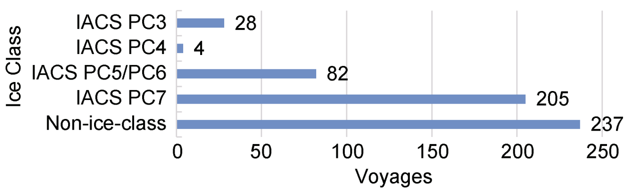



**Figure 4** Ice class of ships transiting the Northeast Passage.

## 2.3 Container ship transits through the Northeast Passage

In 2011, Nornickel's RS (Russian Maritime Register of Shipping) Arc7-class (see Table 1) multipurpose vessel *Zapolyarniy* transported nickel and copper containers to China and returned with consumer goods and equipment to Dudinka Port (Gunnarsson and Moe, 2021). A milestone occurred in 2018 when Maersk Line's RS Arc4-class (see Table 1) container ship *Venta Maersk* became the first container vessel to complete the Arctic route journey, successfully sailing from Busan, Republic of Korea, to Bremerhaven, Germany via the Northeast Passage. Since then, annual container ship transits through the Northeast Passage have been recorded (Figure 5).

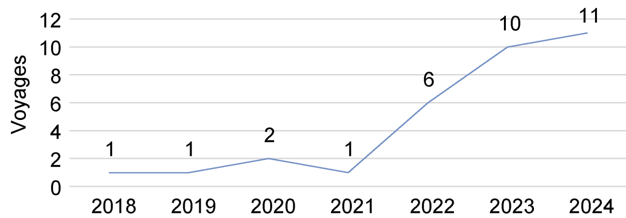



**Figure 5** Number of transit voyages of container ships in the Northeast Passage.

# 3 Pendulum route design for the Northeast Passage

## 3.1 Definition and advantages of the Northeast Passage pendulum routes

### 3.1.1 Definition of pendulum routes

The Arctic routes primarily consist of the Northeast Passage, Northwest Passage, and Transpolar Route. Among these, the Northeast Passage has emerged as the most viable commercial trade corridor due to its superior navigational conditions and more comprehensive infrastructure along the route. Consequently, this study selects the Northeast Passage as its research focus.

According to Li et al.'s (2024) definition of pendulum routes, the Northeast Passage pendulum system involves selecting several hub ports near the ice-free boundaries at both ends of the route. This configuration divides the Asia-Europe shipping route into one ice-covered segment (the Northeast Passage itself) and two ice-free segments. Conventional vessels operate in the ice-free zones, while ice-class ships shuttle between hub ports across the ice-covered section. Figure 6 illustrates this pendulum shipping model.

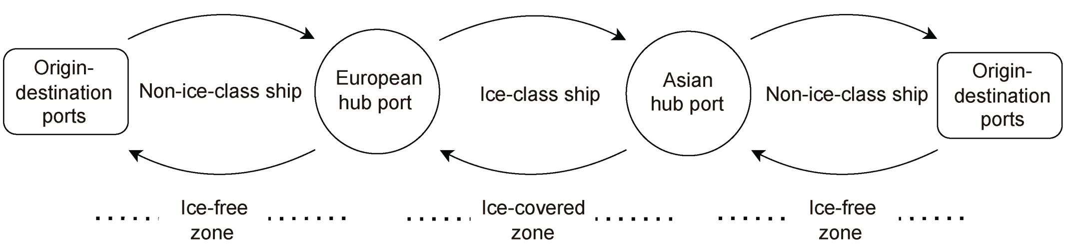



**Figure 6** Pendulum shipping model of the Northeast Passage.

### 3.1.2 Advantages of the pendulum routes

In current Arctic shipping practice, the dominant transportation mode follows the direct route model, where ice-class vessels sail non-stop from origin to destination ports without intermediate port calls. In this model, due to the substantial fuel consumption incurred during the long-distance voyages required of ice class vessels, those with a lower ice class are typically selected to reduce hull weight and overall costs. These technical and economic considerations collectively establish the limited navigation window phenomenon. Beyond this operational window, ice-class vessels face two suboptimal alternatives: either remaining idle (resulting in significant resource underutilization) or redeploying to ice-free zones (where their operating costs substantially exceed those of conventional vessels). The pendulum route system presents an innovative solution: ice-class vessels operate year-round within ice-covered zones while conventional vessels navigate ice-free waters continuously, with cargo transfers occurring at strategically located hub ports. This operational configuration simultaneously enhances the utilization efficiency of ice-class vessels and eliminates the resource waste associated with their high construction costs.

Empirical navigation evidence confirms that individual voyages via the Northeast Passage offer substantial economic advantages. Nevertheless, the restricted navigable window period partially limits the economic gains for shipping enterprises. Establishing regular operations thus represents a pivotal strategy to further improve their profitability. Against the backdrop of global warming, the rapid melting of Arctic sea ice has progressively extended the navigable window of Arctic routes, creating a feasible opportunity for the Northeast Passage to achieve regular operations. In this context, the pendulum route model for the Northeast Passage serves as a viable solution to operationalize regular shipping services.

Furthermore, the pendulum routes enhance intra-Arctic cargo circulation while stimulating freight movement among circumpolar states. By significantly reducing the empty return rate of resource transport vessels, this model further improves shipping efficiency and economic viability.

## 3.2 The design of the pendulum routes for the Northeast Passage

### 3.2.1 Rationale for variant pendulum route designs

Criterion I: Selection of specific shipping routes.

Based on latitude, the Northeast Passage can be divided into three categories:

(1) Low-latitude routes (near-coastal routes, south of 75°N), primarily used by Russian vessels. Due to shallow waters (e.g., Sannikov Strait south of the New Siberian Islands, with a draft limit of <13 m (Verny and Grigentin, 2009)), these routes are typically served by container ships ⩽5000 Twenty-foot Equivalent Unit (TEU) (Xu and Yang, 2020), limiting economies of scale.

(2) Mid-latitude routes (75°N–80°N), traversing the Chukchi Sea, De Long Strait, East Siberian Sea, northern New Siberian Islands, Laptev Sea, Vilkitsky Strait, Kara Sea, and northern Novaya Zemlya. With a minimum depth of approximately 36 m at De Long Strait and moderate ice conditions, this zone is optimal for commercial shipping.

(3) High-latitude routes (80°N–85°N) and near-pole routes (85°N–90°N), which remain ice-heavy in summer and are thus commercially unviable despite shorter distances.

This study focuses on the mid-latitude route of the Northeast Passage.

Criterion II: Selection of sample vessels.

In Arctic shipping practice, the primary transit vessels navigating the Northeast Passage are tankers, bulk carriers, and general cargo ships. Tankers, however, are excluded from this study due to their distinct operational characteristics. Typically deployed on fixed energy transport routes, their navigation patterns are rigidly dictated by the geographical distribution of oil trade. Furthermore, their safety management is subject to stringent International Maritime Organization regulations, creating systemic differences in voyage behavior compared to conventional merchant vessels. Consequently, tankers do not align with the route decision-making dynamics of general cargo shipping.

For bulk carriers and general cargo ships, shared challenges include inefficient cargo handling and elevated risks of freight damage. In contrast, container ships demonstrate significant advantages in economies of scale, offering enhanced transport efficiency, reduced costs, and optimized logistics chains. Through standardized container units, container ships not only improve loading/unloading efficiency and minimize cargo damage but also facilitate logistics standardization and automation. The successful trial voyage by Maersk Line in 2018 conclusively demonstrated the technical feasibility of container ships independently traversing the Arctic route. Therefore, this study selects container ships as the sample vessel type.

Given that the Northeast Passage primarily lies within offshore waters of northern Russia, the RS has established its own ice-class navigation standards. Consequently, this study provides a comparative analysis of ice class standards between IACS and RS, as presented in Table 1.

**Table 1** Ice class standards

| IACS classification | RS classification | Ice conditions |
|---|---|---|
| PC1 | Arc9 | All polar waters |
| PC2 | Arc8 | Moderate multi-year ice |
| PC3 | Arc7 | Second-year ice |
| PC4 | Arc6 | Thick first-year ice |
| PC5/PC6 | Arc5 | Medium first-year ice |
| PC7 | Arc4 | Thin first-year ice |

Generally, higher ice-class vessels exhibit stronger navigation capacity but incur higher construction costs and increased fuel consumption, leading to elevated operational expenses. According to Russian Arctic navigation regulations, even with icebreaker escort, IACS PC7-class vessels cannot navigate under severe ice conditions, whereas IACS PC3 satisfies the required ice-class standards.

Considering the ice-class vessel's navigation capability and costs, this study selects the following vessels:

(1) IACS PC3 container ships as the ice-class sample vessels, with ship parameters provided by collaborative partners of the special subject "Feasibility Study on Regularized Polar Shipping Routes" under the sub-project of Ministry of Industry and Information Technology of China for the "JD Major Technical Equipment Industrialization Project";

(2) *Ever Ulysses* (selected by cargo capacity) as the sample vessel for ice-free waters, with parameters sourced from the maritime database ShipXY (full parameters listed in Table 2).

**Table 2** Technical specifications of sample vessels

| Parameter | Ice-class container ship | Non-ice-class container ship |
|---|---|---|
| Ice class | IACS PC3 | Non-ice class |
| Capacity/TEU | 8,000 | 5,652 |
| Construction cost/USD | 146,167,300 | 58,000,000 |
| Dimensions (length×breadth)/(m×m) | 290×46 | 285×40 |
| Draft/m | 12 | 12.7 |
| Deadweight tonnage/t | 105,000 | 63,216 |
| Gross tonnage/t | 90,000 | 69,246 |
| Net tonnage/t | 48,000 | 30,235 |
| Loading rate | 70% | N/A |
| Fuel consumption/($g{\cdot}kW^{-1}{\cdot}h^{-1}$) | 170 | 180 |
| Main engine power/kW | 381,936 | 48,635 |

Note: USD denotes United States dollar uniformly.

Criterion III: Selection of hub ports.

The pendulum route operation necessitates transshipment between non-ice-class vessels and ice-class vessels, requiring the establishment of hub ports for intermediate handling. The selection of hub ports must consider both operational feasibility and economic efficiency, where feasibility primarily depends on port infrastructure, specifically the following: (1) ice conditions that allow non-ice-class vessels to navigate independently; (2) a maximum allowable draft of 13 m; and (3) container handling capabilities. Regarding economic efficiency, the selection is based on the shipping distance between the hub port and ice-covered areas, as ice-class vessels with reinforced hulls have greater deadweight and consequently higher fuel consumption when transporting equivalent cargo volumes compared to conventional vessels. Since this operational cost is directly correlated with voyage distance, positioning hub ports closer to ice-covered areas theoretically reduces ice-class vessel sailing distances, thereby lowering costs and improving economic efficiency. To evaluate how hub port proximity to ice-covered areas affects economic performance, this study examines two hub ports at each end of the ice-covered region. The selected hub ports are as follows:

Petropavlovsk-Kamchatsky Port (158.65°E, 53.00°N), one of Russia's major Pacific ports, operates year-round with 70 berths spanning 7,310 m and accommodating vessels up to 15 m draft. Its 136.96-hectare facility demonstrates strong handling capacity. With light winter ice conditions, the port enables non-ice-class ships to operate independently (Jiang, 2022). This port represents the closest viable Asian-side location to the ice zone. Hereafter, it will be referred to as Kamchatka.

Vostochny Port (133.05°E, 42.77°N), as the deepest and largest port in the Russian Far East and the terminus of the Trans-Siberian Railway, maintains year-round operations across its 403.58-hectare complex. The port's 32 berths along 6,844.3 m of quay can service ships with drafts up to 17 m. As one of Russia's premier specialized container ports, it experiences only minor floating ice (0.1–0.15 m) from late December through February, permitting independent navigation by non-ice-class ships. This location serves as the second-closest Asian-side option to the ice zone.

Murmansk Port (33.05°E, 68.97°N) benefits from the North Atlantic Current's warming influence, maintaining ice-free operations year-round as Russia's largest Arctic commercial port. Its expansive 645.9-hectare facility contains 111 berths along 13,246.48 m of wharves without draft restrictions, supported by comprehensive modern infrastructure. This strategic location constitutes the closest European-side access point to the ice zone.

Tromsø Port (18.97°E, 69.65°N), another ice-free port due to the Gulf Stream's moderating effects, serves as a key Norwegian Arctic maritime hub. The facility features over 50 berths across 2,100 m of quays with 22-m draft capacity, offering specialized container handling services and advanced warehousing infrastructure. This port represents the second-closest European-side alternative to the ice zone.

### 3.2.2 Design of variant pendulum route solutions

This study selects Shanghai Port (China) and Rotterdam Port (Netherlands) as the origin and destination ports for Asia-Europe cargo transportation. Based on the aforementioned design criteria, with the proximity of hub ports to ice-covered areas as the classification standard, two pendulum route solutions are developed to analyze their differences in shipping economics.

Solution I adopts the closest hub ports to the ice-covered zone at both ends of the Northeast Passage: Kamchatka Port on the Asian side and Murmansk Port on the European side. The specific route is illustrated in Figure 7. Solution II utilizes the secondary closest hub ports to the ice zone: Vostochny Port on the Asian side and Tromsø Port on the European side. The detailed route configuration is presented in Figure 8. The shipping distances between respective ports for both solutions are explicitly annotated in the corresponding figures.

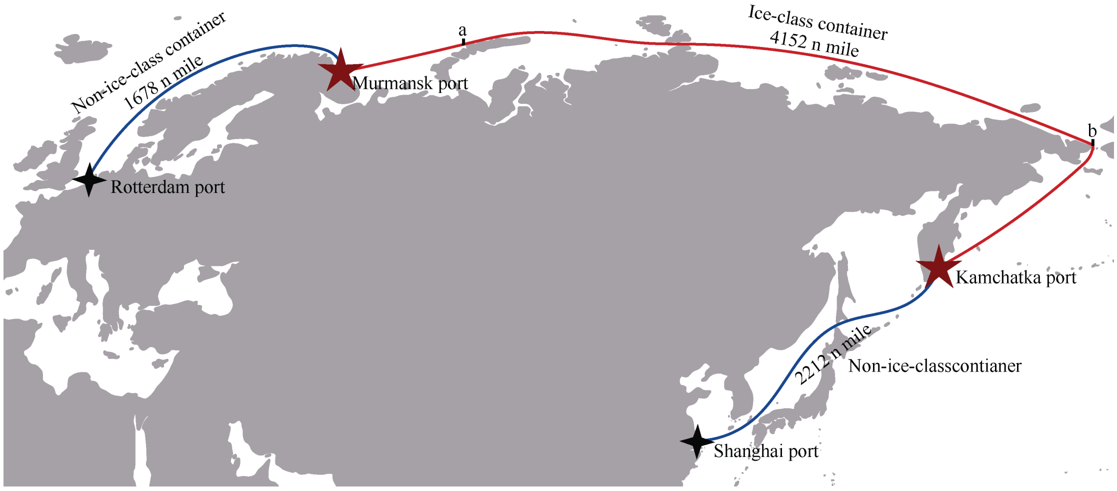



**Figure 7** Solution I specific route and distance.


**Figure 8** Solution II specific route and distance.

In both figures, the red line indicates routes requiring ice-class vessels, and the blue line denotes ice-free routes suitable for non-ice class ships. The segment between "a" and "b" represents ice-covered waters.

# 4 Economic analysis of the Northeast Passage pendulum routes

## 4.1 Fundamental assumptions

Prior to evaluating the economic impacts of different pendulum route solutions on the Northeast Passage, this study establishes the following key assumptions:

Assumption 1: Navigation window hypothesis. Russia's 2013 initiative to develop Type 22220 nuclear-powered icebreakers anticipates a fleet of seven Arktika-class and one Leader-class icebreakers by 2035, with icebreaking capabilities of 2.9 meters and 4.3 meters, respectively. Considering both global warming-induced ice melt and this icebreaker program, we assume year-round navigability (12 months) for the Northeast Passage, enabling continuous operations.

Assumption 2: Port handling time hypothesis. Incorporating modular transportation technology (Li et al., 2024), each hub port is assumed to have four shore cranes with a handling efficiency of 65 TEU·h$^{-1}$. Consequently, handling 5,600 TEU requires approximately 43.1 h. Referencing global container vessel schedule reliability in 2024 from the Shanghai Shipping Exchange, we assume a rounded 3-d port stay duration at hub ports based on the loading/unloading time with added buffer time.

Assumption 3: Vessel speed hypothesis. Container ships maintain speeds between 13 to 25 kn in open waters. Ice-class vessels' speeds in ice-covered zones depend on ice conditions: when icebreaker-escorted, their speed equals the icebreaker's speed. Ice-zone navigation speed follows Jiang and Hu's (2021) formula:

$$V_j = 0.0027 \times I_{nj}^3 - 0.0398 I_{nj}^2 + 0.2489 \times I_{nj} + 3.8385 \quad (1)$$

where $V_j$ container ship speed in the Northeast Passage for month $j$, $I_n$ denotes ice values calculated per the Canadian Arctic Ice Regime Shipping System.

Assumption 4: Insurance cost hypothesis. We assume shipping companies insure vessels at construction cost, with insurance premiums calculated accordingly.

## 4.2 Economic evaluation of shipping operations

### 4.2.1 Selection of economic evaluation metrics

In assessing the economic viability of Arctic routes, existing literature primarily employs two categories of economic indicators: shipping costs and shipping profits. Among these, single-voyage shipping costs serve as the foundation for calculating other cost metrics, while annual profits better reflect the impact of vessel turnover frequency on shipping economics. Building upon the fundamental assumptions established earlier and considering the characteristics of these two evaluation metrics, this study selects annual profit as the primary economic evaluation indicator, with shipping costs being inherently reflected in the profit calculations. Furthermore, to account for the time value of money, this study incorporates the NPV of shipping income as an additional economic evaluation metric. By discounting future earnings to their present value, this approach provides a comprehensive assessment of the overall economic returns of the Northeast Passage pendulum routes throughout the vessel's entire lifecycle, thereby evaluating its long-term operational economic performance.

The NPV of a Northeast Passage pendulum route solution represents the difference between the present value of future cash inflows (shipping revenues) and the present value of corresponding future cash outflows (shipping costs excluding fixed asset depreciation) over a specified period (the vessel's entire lifecycle). This differential reflects the net benefits that the pendulum route solution can generate while considering the time value of money. A higher NPV indicates stronger profitability for the given solution.

### 4.2.2 Shipping economic evaluation model

The single-voyage transportation cost ($C_t$) comprises three components: capital costs (vessel depreciation $C_1$ or charter hire), operational costs (insurance premiums $C_2$, maintenance fees $C_3$, and crew wages $C_4$), and voyage costs (fuel expenses $C_5$, icebreaker escort fees $C_6$, and port charges $C_7$). The cost model is expressed as Equation (2):

$$\begin{aligned} C_t &= C_1 + C_2 + C_3 + C_4 + C_5 + C_6 + C_7 \\ &= \frac{K\times(1-\eta)}{L}\times T + \frac{K\times I}{360}\times T + \frac{K\times M}{360}\times T + \frac{W\times N_c}{30}\times T + \\ &\quad P_b\times F\times T + Z\times R_i\times G + G\times\varphi \end{aligned} \tag{2}$$

where $K$ denotes vessel construction cost, $\eta$ the net residual value rate, $L$ the vessel service life, $I$ the annual insurance rate, $M$ the annual maintenance cost, $W$ the monthly crew salary, $N_c$ the number of crew members, $P_b$ the bunker price, $F$ the daily fuel consumption, $T$ the single-voyage duration, $Z$ the number of icebreaker escort zones, $R_i$ the icebreaker escort fee rate, $G$ the gross tonnage, and $\varphi$ the transit fee rate.

Considering environmental conditions along Arctic routes, crew wages are adjusted upward by 3%. Wage data are obtained from the China (Shanghai) International Seafarer Salary Scale published by the Shanghai Shipping Exchange (January–December 2023). The salary of a single voyage crew member is shown in Equation (3):

$$W_v = \frac{W_m}{30}\times T \tag{3}$$

where $W_v$ denotes the single-voyage crew wages, $W_m$ the total monthly crew wages, one month is calculated as 30 d.

In light of the heavy fuel oil ban, this study exclusively employs Very Low Sulfur Fuel Oil (VLSFO). Monthly VLSFO prices at Shanghai and Rotterdam ports from 2020 to 2023 are sourced from Clarksons Intelligence Network. The fuel consumption rate is calculated according to the propeller law (Hu, 2024) as shown in Equation (4):

$$F_{rj} = S\times H_j = S\times\frac{H_{max}}{V_{max}^3}\times V_j^3 \tag{4}$$

where $F_{rj}$ the fuel consumption rate (g·h$^{-1}$) for month $j$, $S$ specific fuel consumption (g·kW$^{-1}$·h$^{-1}$), $H$ brake horsepower (kW), $V_j$ container ship speed in the Northeast Passage by month (actual speed in ice-free zones regardless of month), $H_{max}$ maximum continuous rating of main engine, and $V_{max}$ maximum vessel speed.

The transportation profit ($P$) is calculated as the difference between transportation revenue ($R_t$) and transportation costs ($C_t$), where $C_t$ is inherently incorporated in $P$. Transportation revenue equals the product of the container freight rate ($R_f$) and container load quantity ($Q$). Container freight rates are obtained from Clarksons Intelligence Network. The annual profit model is expressed in Equation (5):

$$P = R_t - C_t = R_f\times Q - C_t \tag{5}$$

The NPV model is given by Equation (6):

$$V_P = \sum_{t=1}^{20}\frac{P_t + C_{1t}}{(1+r)^t} - K \tag{6}$$

where $V_P$ represents NPV, $K$ vessel construction cost, $P_t$ the annual transportation profit in year $t$, $C_{1t}$ vessel depreciation in year $t$ (the sum of $P_t$ and $C_{1t}$ equals the net cash inflow in year $t$), and $r$ the discount rate, for which this study adopts the 2023 average yield of China's 1-year government bonds (2.11%).

In this study, we employ EViews software to perform descriptive statistical analyses on three key variables: container freight rates, VLSFO fuel prices, and monthly wages. These analyses yield their respective distribution ranges. Building on our earlier speed assumptions, we establish speed distribution parameters for ice-class container vessels in ice-covered waters and for both ice-class and non-ice-class container vessels in open waters. According to monthly ice conditions along the Northeast Passage and IACS PC3-class vessel specifications, we identify that a maximum of three escorting zones require icebreaker escort during February–May, with no escort needed in other months. The corresponding escort fees are calculated using Russia's icebreaker pricing system. For port charges, we derive loading/unloading fee distributions from tariff schedules of major Asian, European, and North American ports. We compute other port fees based on individual port regulations. The distribution ranges and parameter settings for all variables are presented in Table 3, where "U" denotes uniform distribution, specifically defined as U(minimum value, maximum value); and "N" represents normal distribution, defined as N(mean, standard deviation) [minimum value, maximum value].

**Table 3** Parameter settings and distribution ranges

| Parameter or variable | Setting or distribution range |
|---|---|
| Depreciation | Straight-line method with 5% residual value rate over a 20-year service life |
| Insurance rate | 1.5% of the vessel construction cost |
| Maintenance rate | 2.5% of the vessel construction cost |
| Crew salary/USD | N(84,131.83, 3,776.46) [79,987, 91,104] |
| Ice-zone speed/kn | U(3.5, 17.1) for Feb–May, U(5.6, 18) for Jun–Jan |
| Open-water speed/kn | U(13, 20) for ice-class ships, U(13, 25) for non-ice-class ships |
| Bunker price/USD | Shanghai: N(600.39, 190.08) [254.19, 1,122.19]<br>Rotterdam: N(533.23, 165.49) [210.69, 911.19] |
| Escorting zones count | U(0, 3) |
| Escorting tariff/($USD \cdot GT^{-1}$) | Positively correlated with escorting zones:<br>0 zones—0, 1 zones—6.43, 2 zones—7.72, 3 zones—9. |
| Handling charge/($USD \cdot TEU^{-1}$) | Shanghai and Russian ports: U(66.7, 89.4)<br>Rotterdam and Norwegian ports: U(89.4, 287.23) |
| Freight rate/($USD \cdot TEU^{-1}$) | N(1,796.93, 2,084.41) [223.5, 7,784.25] |
| Discount rate | 2.11% |

#### 4.2.3 Sensitivity analysis model

The development and utilization of the Arctic routes are influenced by the maritime environment, leading to uncertainties. The Monte Carlo simulation method has been employed for economic analysis, preliminarily reducing the impact of some uncertain factors (such as fuel prices). However, the values of certain key parameters remain insufficiently precise. By applying the Sensitivity Analysis method, the magnitude of influence caused by variations in these factors can be determined. The calculation formula is as follows:

$$S_a = \frac{\Delta A/A}{\Delta Y/Y} \tag{7}$$

where $S_a$ is the sensitivity coefficient, $\Delta A/A$ the change rate of the evaluation index, $\Delta F/F$ the change rate of the independent variable. When $S_a$ is positive, it indicates that the evaluation index changes in the same direction as the independent variable; conversely, a negative value suggests an inverse relationship.

### 4.3 Economic calculation and results analysis of shipping operations

#### 4.3.1 Economic analysis

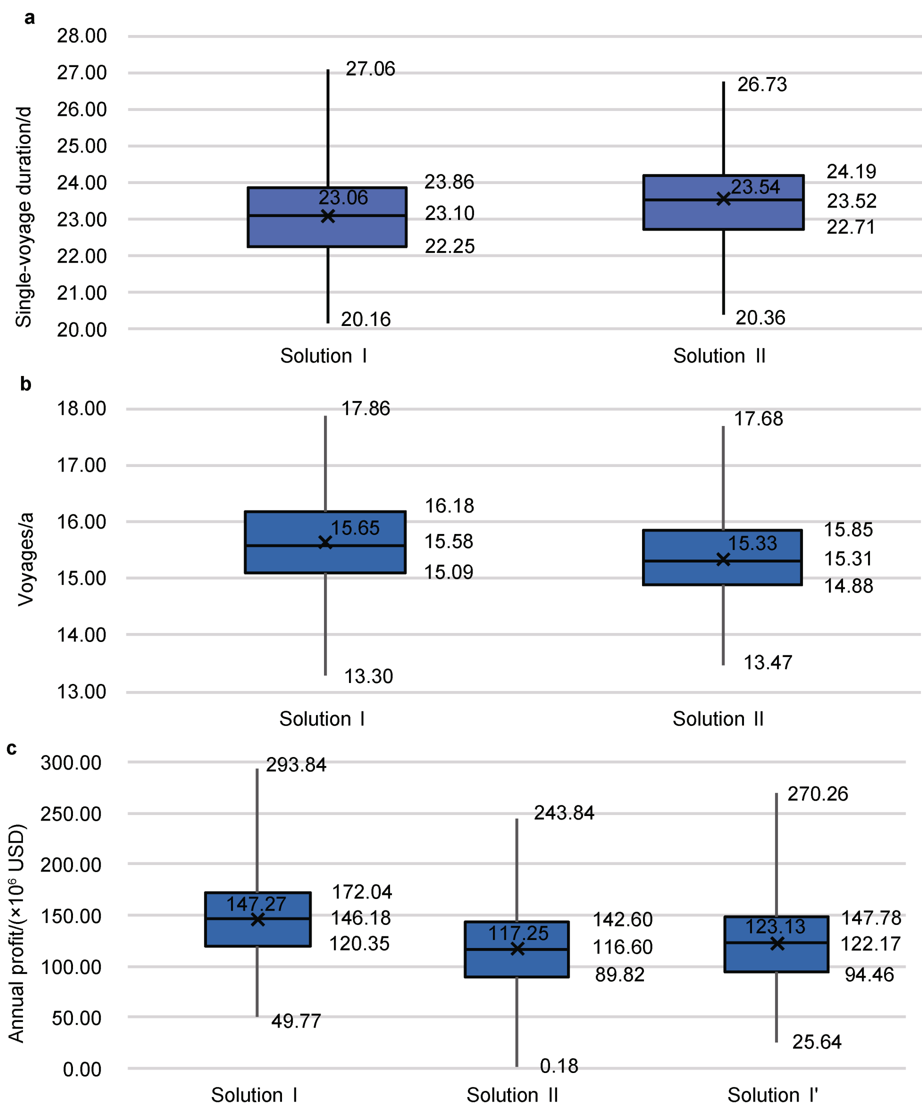
Given the considerable uncertainty inherent in the economic components of the Northeast Passage pendulum routes, this study employs Crystal Ball software to conduct Monte Carlo simulations for economic evaluation. The distribution ranges of uncertain variables and target equations were input into Crystal Ball, generating 20,000 sets of hypothetical variable samples and their corresponding predicted variable values. To more clearly demonstrate the impact of hub port proximity to ice-covered zones on shipping economics, we introduce an additional solution labeled "Solution I′" where port charges are assumed identical to those in Solution II. Table 4 presents the predicted expected values of single-voyage shipping costs, derived by dividing annual data totals by the number of voyages per year.

**Table 4** Expected shipping costs for different pendulum route solutions (unit: USD)

| Cost item | Solution I | Cost share | Solution II | Cost share | Solution I′ | Cost share |
|---|---|---|---|---|---|---|
| Depreciation | 342,232 | 6.92% | 393,970 | 5.76% | 343,182 | 5.29% |
| Insurance | 108,073 | 2.19% | 124,412 | 1.82% | 108,373 | 1.67% |
| Maintenance | 180,122 | 3.64% | 207,353 | 3.03% | 180,622 | 2.78% |
| Crew wages | 66,380 | 1.34% | 67,776 | 0.99% | 66,522 | 1.03% |
| Fuel cost | 559,093 | 11.31% | 792,404 | 11.59% | 557,538 | 8.59% |
| Icebreaking escorting fees | 172,854 | 3.50% | 173,625 | 2.54% | 173,625 | 2.68% |
| Port charges | 3,516,680 | 71.11% | 5,073,932 | 74.21% | 5,073,932 | 78.18% |
| Total voyage cost | 4,945,434 | 100.00% | 6,837,681 | 100.00% | 6,489,706 | 100.00% |

As evidenced in Table 4, port charges constitute the largest proportion of total shipping costs. This results from the transshipment operations at two hub ports inherent in the pendulum route design, which significantly increase handling charges. Solution II demonstrates higher overall port charges compared to Solution I. Fuel costs represent the second-largest cost component in the shipping expenditure structure. When port charges are equalized between solutions, Solution I′ demonstrates a reduction of 348,000 USD (5.09% decrease) in expected single-voyage shipping costs compared to Solution II. This cost advantage is attributed to Solution I's hub ports being located closer to ice-covered zones, which substantially reduces the sailing distance for ice-class vessels. Specifically, the shorter distance results in an expected fuel consumption saving of approximately 429.90 t per voyage, leading to a 233,300 USD reduction (29.44% decrease) in expected single-voyage fuel costs relative to Solution II. Furthermore, as shown in Equation (2), insurance and maintenance costs depend solely on vessel construction cost, rate, and sailing time. The expected values of these costs per voyage for Solution I are significantly lower than those for Solution II. Given identical construction costs and rates, this indicates that Solution I has a shorter expected sailing time per voyage and consequently a higher expected annual voyage frequency than Solution II, which will be demonstrated more clearly in the subsequent analysis.

Figure 9 illustrates the economic evaluation results of different pendulum route solutions. In the figure, panels a and b present the operational performance metrics for both pendulum route solutions. Solution I achieves an expected single-voyage duration of 23.06 d with 15.65 annual voyages, whereas Solution II shows 23.54 d and 15.33 voyages, respectively. These results confirm that Solution I provides both shorter voyage durations and higher annual voyage frequency compared to Solution II. Figures 9c and 9d accordingly present the evaluation results for annual profit and NPV.



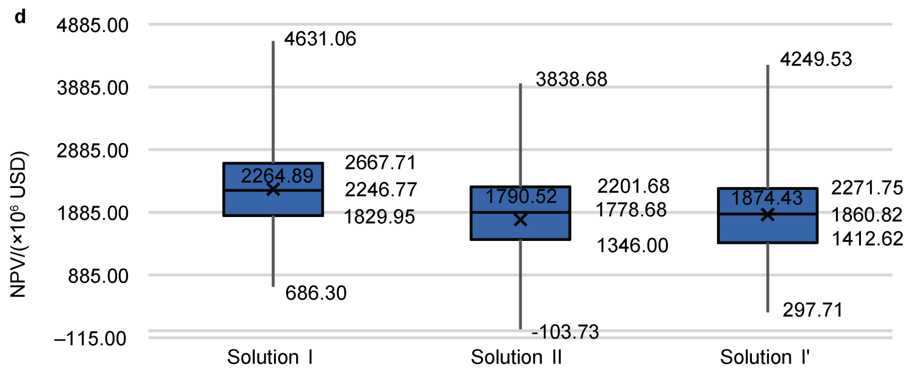



**Figure 9** The economic evaluation results of different pendulum route solutions for shipping. **a**, the evaluation result of single voyage duration; **b**, the evaluation result of annual voyage frequency; **c**, the evaluation result of annual profit; **d**, the evaluation result of NPV.

The evaluation results demonstrate that both pendulum route solutions exhibit a high probability of economic viability, with Solution I showing overall superior economic performance. Solution I achieves a 100% probability of positive annual profits, with a 95% confidence interval (95% CI) ranging between 77.0923 million USD and 232.9143 million USD, while maintaining a 100% probability of positive NPV. For Solution II, the probability of positive annual profits reaches 99.964% (95% CI: 47.0895–198.7509 million USD), with a 99.929% probability of positive NPV.

Under the assumption of equal port charges, Solution I′ maintains its economic advantage through reduced fuel consumption resulting from the closer proximity of its hub ports to ice-covered zones. Compared to Solution II, Solution I′ demonstrates a 5.8866 million USD (5.02%) increase in expected annual profits and an 83.9135 million USD (4.69%) improvement in expected NPV, while achieving a 100% probability of positive NPV. These findings confirm the theoretically anticipated negative correlation between hub port proximity to ice-covered zones and the economic performance of Northeast Passage pendulum routes.

### 4.3.2 Sensitivity analysis

In Section 4.1, we assumed a port stay duration of 3 d at the hub port. However, this value was obtained through estimation and inevitably differs from real-world data. To address this, we conducted a sensitivity analysis using the predicted expected value from the economic analysis as the baseline, assessing the impact of changes in port stay duration on the results. The sensitivity analysis results are presented in Table 5.

As shown in Table 5, the economic fluctuation range of Solution I is generally smaller than that of Solution II, demonstrating greater robustness and a better ability to withstand adverse impacts caused by variations in the uncertain parameter (port stay duration). When this parameter increases from 3 to 9 d, both solutions experience significant reductions in annual profit and NPV. Notably, Solution II shows a 33.71% decrease in NPV (equivalent to a one-third loss). Should such extreme conditions occur in actual operations, temporarily diverting to alternative hub ports might serve as a viable remedial measure.

**Table 5** Sensitivity analysis on port stay duration changes

| Port stay duration/d | | Annual profit | | NPV | |
|---|---|---|---|---|---|
| | | Change ratio | $S_a$ | Change ratio | $S_a$ |
| Solution I | 1 | 15.62% | −0.234 | 16.87% | −0.253 |
| | 5 | −12.16% | −0.182 | −13.13% | −0.197 |
| | 7 | −21.89% | −0.164 | −23.65% | −0.177 |
| | 9 | −29.86% | −0.149 | −32.25% | −0.161 |
| Solution II | 1 | 15.91% | −0.239 | 17.53% | −0.263 |
| | 5 | −12.43% | −0.186 | −13.70% | −0.205 |
| | 7 | −22.41% | −0.168 | −24.69% | −0.185 |
| | 9 | −30.60% | −0.153 | −33.71% | −0.169 |

## 5 Conclusion

This study selects hub ports through a comprehensive consideration of both feasibility and economic factors, and then designs Northeast Passage pendulum route solutions based on the proximity between hub ports and ice-covered waters. Utilizing a Monte Carlo simulation, we conduct a comparative analysis of the shipping economic performance between the two pendulum route solutions using annual profit and NPV as evaluation metrics. The main findings are as follows: First, both Northeast Passage pendulum route solutions demonstrate favorable shipping economics in most conditions, with Solution I exhibiting consistently superior performance compared to that of Solution II. This economic advantage derives from two key factors: Solution I's substantially lower port charges (constituting the predominant cost component) and its strategically positioned hub ports in closer proximity to ice-covered areas. Second, an inverse relationship exists between hub port distance from ice zones and shipping economic efficiency. This correlation operates through dual mechanisms:

(1) The elevated fuel consumption of ice-class vessels compared to standard vessels means that reduced ice-zone navigation distances—achieved through optimal hub port placement—directly decrease fuel expenditure, thereby lowering aggregate operational costs.

(2) Given that ice-class vessels have a lower cruising speed than conventional ones, a reduction in their sailing distance translates into shorter voyage durations, higher annual voyage frequency, and ultimately, greater revenue.

Based on these findings, shipping companies utilizing the Northeast Passage for cargo transportation may consider adopting pendulum route configurations to achieve year-round operational continuity and enhance economic returns. When selecting hub ports, priority should be given to those located closer to ice-covered areas, provided other conditions remain comparable, as this strategic positioning reduces ice-class vessels' navigation distance through ice zones, thereby optimizing overall operational efficiency and cost-effectiveness.

The indirect estimation of Arctic port stay duration in this study presents limitations, warranting improved data accuracy in future research.

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