Ocean Engineering 304 (2024) 117747

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

Research paper

Optimizing the scheduling scheme for NSR/SCR tramp vessel shipping between Asia and Europe

Chengcheng Liu [a], Yanjie Zhou [a,*], Zhongzhen Yang [b], Yumin Li [a], Tao Li [a]

[a] School of Management, Zhengzhou University, Zhengzhou, 450001, China
[b] Faculty of Maritime and Transportation, Ningbo University, Ningbo, 315211, China

ARTICLE INFO

Keywords:
Northern Sea Route
Suez Canal route
Tramp vessel scheduling
Vessel with ice-breaking ability

ABSTRACT

To optimize the scheduling scheme of tramp vessels between Asia and Europe, considering the opening of the Arctic route, a vessel scheduling management optimization model is developed from the perspective of shipping companies. Based on meeting the shippers' requirements for transportation between Asian and European ports, minimizing the total cost of multi-period operation of tramp vessels, the specific transport scheduling scheme for ships is obtained. We found that shipping companies building their Vessels with Ice-breaking Ability (VIA) can reduce the total cost of ships operating Asia-Europe routes throughout the year. Furthermore, in the event of a half increase in fuel prices, opting for Arctic routes during the winter season proves to be more cost-effective for shipping companies.

1. Background

Shipping management is important in maritime industry (Zhou and Kim, 2020a, 2020b), especially for shipping network design. Sea ice extent has been declining in the Arctic with the fastest-warming region extension, which extends the navigation period of the Northern Sea Route (NSR) (Han, 2020). Compared to the traditional Suez Canal Route (SCR), the voyage of a vessel to Europe via the NSR can be shortened by 40% (Xu and Yu, 2022). Currently, the Arctic shipping routes are navigable from early August to mid-October. The navigation period will be shortened with cold weather extension during wintertime, which deteriorates the economic indicators for freight transport through NSR (Dmitrenko et al., 2022). This short period of navigable routes cannot satisfy the tendency of the global shipping volume to increase (Skripnuk et al., 2020). Governments and logistics companies explore all the possibilities to increase the navigable period of Arctic routes. While attending the Belt and Road Forum in October 2023, The Russian president announced that the Northern Sea Road will be open to ice-breaking cargo ships throughout the year from 2024. The VIA, designed to enable sailing through ice-covered areas, is vital for shipping companies, which must invest more capital in adopting VIAs for going through NSR. Concerning the use of VIAs on the Arctic route, Dmitrenko et al. (2022) analyzed the feasibility of VIAs for passage through the NSR during wintertime. Considering the operational behavior of shipping companies, shipping companies need to redesign their shipping routes under the circumstance that the year-round navigation of the Arctic route is available. This paper focuses on the economic viability of shipping companies using VIAs under such circumstances.

A more extended navigation period of the NSR is becoming possible soon (Peng et al., 2020). With year-round access becoming possible, many shipping companies have reconsidered whether to adjust their shipping routes or not. Many previous studies focused on rationalizing the use of the Arctic route to make it more economical. Furuichi and Otsuka (2015) and Xu et al. (2018) proposed a seasonal NSR/SCR (Suez Canal Route)-combined shipping service linking Shanghai and Rotterdam where cargoes are shipped via NSR in the summer and SCR in the winter, respectively. Faury et al. (2020) defined the best option for mixing the shipping lane (NSR or SCR) for oil producers operating in the Russian Arctic zone in 2013–2057. This paper focuses on the problem of optimizing vessel scheduling while performing mixed NSR/SCR route selection under the assumption that both NSR and SCR are navigable throughout the year.

This study assumes that both the NSR and the SCR are navigable year-round. In this context, a shipping company is providing cargo transportation services between Asia and Europe. The shipping company needs to determine the number of VIAs in its mixed fleet (part of the

* Corresponding author.
E-mail addresses: chengyulcc@gs.zzu.edu.cn (C. Liu), ieyjzhou@zzu.edu.cn (Y. Zhou), yangzhongzhen@nbu.edu.cn (Z. Yang), liyumin@zzu.edu.cn (Y. Li), taoli@zzu.edu.cn (T. Li).

https://doi.org/10.1016/j.oceaneng.2024.117747
Received 20 February 2024; Received in revised form 25 March 2024; Accepted 1 April 2024

vessel has VIA functionality), and shipping routes, considering the loading/unloading demand and time windows. The shipping company aims to minimize the total costs of the mixed fleet.

The contributions of this paper are summarized as follows: (1) We introduce a novel problem concerning the scheduling of tramp vessels between Asia and Europe, incorporating the option for selective passage through the NSR or the SCR under the assumption of year-round navigability in the Arctic route. To the best of our knowledge, this problem has not been previously analyzed, making our research the first of its kind in this area. (2) A nonlinear integer programming model is proposed to formulate the studied problem by minimizing the total shipping cost, which will output the ports of loading and unloading of the vessel and their corresponding arriving time, the volume of cargo loaded and discharged in the ports, the total operating costs and costs of each component. (3) To make the nonlinear integer programming model solvable by modern solvers, such as Cplex, and CBC, a linearization model is proposed to simplify the model. (4) A case study is conducted by using a shipping company's actual freight demand date. Various sensitive analyses are also made for analyzing the parameters changing of ice-breaking pilotage fee and fuel price. (5) This paper gave beneficial conclusions, which could help shipping companies determine the shipping network. As the ice-breaking pilotage fee increases, it becomes progressively less economical for vessel operators to build VIAs. This paper provides a theoretical basis for whether it is feasible for shipping companies to construct ice-breaking vessels for navigation.

The remainder of this paper is organized as follows. Section 2 presents the literature review. The problem description and mathematical formulation of the studied problem are shown in section 3. A case study is presented in section 4. Finally, the conclusions and discussions are given in section 5.

2. Literature review

Studies on the Tramp Ship Scheduling Problems (TSSPs), A typical TSSP is the earliest described by Appelgren (1969). Since then, many scholars have discussed TSSPs based on the variation of different factors, the vessel speed is one of them. Norstad et al. (2011) and Tang et al. (2013) proposed a vessel speed optimization model with tramp ship scheduling based on different algorithms respectively. M. Li et al. (2022) and Wang and Chen (2020) and Wen et al. (2016) further consider the fuel price on their basis. The time window of the vessel is another factor about TSSPs that many researchers focus on. Castillo-Villar et al. (2014) and de Armas et al. (2015) addressed the TSSPs with a time window for ship discretization and solved with the corresponding algorithm. Fan et al. (2021) considered the factors of the satisfaction of the cargo owner and solved the TSSPs in a fuzzy time window. Based on considering the strict time window, Yang et al. (2021) optimized the tramp ship scheduling by reducing the waiting time for ship unloading.

However, in the above studies, no scholars pay attention to the problem of vessel route selection about TSSPs at present, the routes between two ports are unique in terms of ship route selection, and there is no literature on ships choosing different routes between two ports at the same time. Considering that the NSR will soon be open all year round, the NSR is likely to form a trend of equal rival with the SCR, so in the optimization of TSSPs between Asia and Europe, we considered the question of the selection of NSR and SCR for vessels at the same time so that the shipping company can get the best transportation scheme throughout the year.

Furthermore, a large body of literature has studied the economic or navigational viability of the NSR, but few literatures have studied water path planning based on NSR ice sheet conditions (Shu et al., 2023; Zhang et al.,2019, 2022; Lee et al.,2018, 2021). A recent review can be found in (Milakovic et al., 2018; Theocharis et al., 2018; Meng et al., 2017), most of which have studied the economic feasibility of the NSR from both the sea ice situation and a commercial perspective, while we only discuss the commercial perspective. Wan et al. (2018) and Han (2011) calculated the one-way transport cost of a ship through NSR versus SCR and found by comparison that NSR is uneconomic compared to SCR. However, they are both based on a single voyage of the ship and do not consider the ship scheduling for a long time, thus the results obtained are out of touch with reality. Liu and Kronbak (2010) elucidated the circumstances under which NSR is competitive compared to SCR based on the length of the seaworthy season for NSR. However, this paper discusses TSSPs from the perspective of year-round navigation, which makes up for the defects of seasonal navigation.

Schoyen and Brathen (2011) suggested that the Arctic route is suitable for tramp ship traffic in the early days. They argue that the NSR is better suited to bulk cargoes than container liner shipping. In recent years, an increasing number of scholars have developed issues related to the NSR of tramp ship traffic. The NSR has seasonal advantages for bulk carrier traffic in the short term, or could be used as a substitute route for the SCR (Theocharis et al., 2019). However, at present, most of the literature studies liner transportation in the NSR (Zhang et al., 2016; L. Li et al., 2022; Liu et al., 2021), there are few kinds of literature on the optimization of TSSPs, Li et al. (2020) made decisions on the TSSPs with uncertain cargo availability of future via the NSR. M. Li et al. (2022) took into account CO2 emissions on their basis. This paper establishes a year-round Asia-Europe TSSP model from the point of view of shipping companies and makes a vessel decision on the choice between SCR and NSR based on satisfying the cargo time window.

In addition, the year-round availability of NSR has led shipping companies to pay more attention to the construction of VIAs. Although the use of icebreakers will greatly reduce the cost of icebreaking pilotage, the huge cost of building VIAs has forced shipping companies to weigh its economics. Therefore, it is essential to explore the question of whether shipping companies should build their VIAs. This is also one of the highlights of this paper.

In conclusion, this paper primarily introduces the following innovations (contributions): (1) Introducing and solving a new problem. Currently, scholars mainly focus on the economic aspects of optimizing irregular ship scheduling between Asia and Europe on a single route. This study approaches the optimization of year-round transportation scheduling between Asia and Europe using both the Suez Canal and the Arctic route from the perspective of shipping companies. This has implications for future decision-making by shipping companies on whether to build vessels with ice-breaking ability and optimize ship scheduling if conditions for Arctic navigation improve. (2) From a theoretical perspective, if we abstract the above real-world problem into a classic transportation problem, the new problem we propose can be considered an extension of the Capacitated Vehicle Routing Problem with Time Windows (CVRPTW). However, unlike the CVRPTW problem, the practical problem we address involves route selection (Suez Canal route and Arctic route), which is a CVRPTW problem with path selection, and no researchers have studied it yet. (3) Existing research on the Tramp Ship Scheduling Problem (TSSP) mainly focuses on decision variables such as port calls, time spent at ports, and cargo volumes handled at ports. In this study, we add a decision variable related to whether it is necessary to self-build vessels with ice-breaking ability when the Arctic route allows year-round navigation.

3. Problem description and mathematical model

3.1. Problem description

When transporting cargo between Asia and Europe, a shipping company usually needs to determine choosing the Arctic route or the Suez Canal route, which are the only two optional routes between Asia and Europe continents. Choosing the Arctic route will reduce the shipping time compared with adopting the Suez Canal route. Taking the example of a voyage from Shanghai to Hamburg, shipping on the NSR can save up to 14 days over the SCR (https://www.forbes.com). However, the vessels going through the NSR need VIAs during the winter season. Reducing carbon emissions and time efficiency are two main benefits of using vessels that are capable of breaking through moderate ice thicknesses to transit cargo through NSR. However, a VIA through moderate ice thicknesses needs more investments compared with vessels without ice-breaking ability.

In February 2021, a large commercial cargo vessel completed the NSR for the first time in the middle of winter. Many companies have expressed their intention to develop the NSR for all seasons by using VIA. Thus, a company needs to explore how many VIAs and ordinary vessels to satisfy the all-season customer demand by minimizing the capital cost of vessels, transportation cost, port cost, and ice-breaking pilotage fee of the NSR.

There is a large difference in the cost of shipping via NSR in summer versus winter due to differences in sea ice conditions. Therefore, we divide the year into two time periods for vessel scheduling: summer-autumn and winter-spring to discuss the impact of VIAs. We assume that the Arctic route and Suez Canal route are navigable for all-season, there are n bills of cargo with the planning horizon in the Asia-Europe bulk tramp market, labeled as i, the loading and unloading ports corresponding to cargo i are labeled as i and $(n+i)$. D_l and D_u are the sets of loading ports and unloading ports respectively. P^A and P^E are the sets of Asian ports and European ports respectively. Assume that the shipping company has N vessels to complete these cargo shipments. The initial ports for vessels $o(v)$ are given and selected by loading ports of cargoes.

A small case is shown in Table 1. There are 5 bills of cargo ($n=5$) in the Asia-Europe bulk market and a shipping company completes cargoes with 3 vessels. Note that different loading and unloading ports can correspond to ports with the same geographical location. The specific route design of this paper is shown in Fig. 1.

3.2. Model assumptions

The following assumptions are made:

1. A shipping company has mixed fleets with types of vessels. Only a portion of the vessels have the ice-breaking ability and the other does not. The ice-breaking capacity and capital cost of the two vessel types are different. The carrying capacity, speed, draft, and other parameters are the identity;
2. Each dry bulk cargo can only be transported by one vessel, not in batches;
3. The initial port for each vessel is given. After completing a voyage, it is not necessary to return to the initial port; No consideration of cargo handling time.

3.3. Symbol description

Before introducing the details of the mathematical model, the sets, indexes, and parameters are listed as follows.

Sets	
V	The set of vessels
N	The set of cargoes
D_l	The set of loading ports
D_u	The set of unloading ports
$o(v)$	The set of initial ports for vessels
P^A	The set of Asian ports
P^E	The set of European ports
D	The set of loading and unloading ports, $D = D_l \cup D_u$
P	The set of all ports in the transport network, $P = D \cup o(v)$
A	The set of arcs (i,j) that vessels can navigate $(i,j \in P)$
Indexes	
i	Index of cargoes and loading ports
j	The different port with i in the transport network
v	Index of vessels
Parameter	
d_{ij}^A	The distance between Asian ports i and j $(i,j \in P^A)$
d_{ij}^E	The distance between European ports i and j $(i,j \in P^E)$
d_{ij}^{NAE}	The distance from ports i to j through the Arctic route $(i \in P^A, j \in P^E)$
d_{ij}^{NEA}	The distance from ports i to j through the Arctic route $(i \in P^E, j \in P^A)$
d_{ij}^{SAE}	The distance from ports i to j through the Suez Canal route $(i \in P^A, j \in P^E)$
d_{ij}^{SEA}	The distance from ports i to j through the Suez Canal route $(i \in P^E, j \in P^A)$
q_i	Quantity of cargo i $(i \in D_l)$
p_i	One-time port fee paid by the vessel to the port at port i $(i \in D)$
w_i	The cost of loading and unloading per ton of cargo at port $i (i \in D)$
ET_i	The earliest time that vessels are allowed to arrive at port i $(i \in D)$
LT_i	The latest time that vessels are allowed to arrive at port i $(i \in D)$
s	Speed of vessel
C^n	The capital cost of the ordinary vessel
C^{ts}	The Suez Canal toll
C^{tos}	The Arctic Route ice-breaking pilotage fee for ordinary vessel in summer
C^{tow}	The Arctic Route ice-breaking pilotage fee for ordinary vessel in winter
C^{tiw}	The Arctic Route ice-breaking pilotage fee for VIA in winter
V^{cap}	The maximum load capacity of vessel
N	Number of vessels in operation
P^f	The fuel price
μ	Fuel consumption coefficient of the vessel
k	The payload of vessel
w	The lightship weight of vessel
β	The VIA building coefficient

(continued on next column)

(continued)

The decision variables, derived variables, and auxiliary variables are listed as follows.

Decision variables	
x_{ijv}	Be equal to one if the vessel v sails from port i to port j and zero otherwise $(i,j \in P)$
y_v	Be equal to one if the vessel v is a VIA and zero otherwise $(v \in V)$
t_{iv}	The time when vessel v arrives at port i $(i \in D)$
z_{ij}^{AE}	Be equal to one if the vessel sails from port i to j via the Arctic route $(i \in P^A, j \in P^E)$
z_{ij}^{EA}	Be equal to one if the vessel sails from port i to j via the Arctic route $(i \in P^E, j \in P^A)$
I_{iv}	Be equal to one if the vessel v docked at destination port i finally $(v \in V, i \in D_u)$
u_{iv}	The order in which vessel v visits port i $(v \in V, i \in P)$
Derived variables	
q_{ijv}	The weight of cargo i loaded by vessel v at port i to port j $(i \in D_l, j \in D, v \in V)$
$d_{ij}(x_v, z_v)$	The distance from port i to port j $(i,j \in P, v \in V)$
Auxiliary variables	
l_{iv}	Total cargo quantity when vessel v leaves port i $(v \in V, i \in D)$

3.4. The mathematical model

$$Min \sum\nolimits_{v\in V}\left(\underbrace{C_{ij}^{f}(x_v,z_v)}_{fuel\ cost}+\underbrace{C_v(y_v)}_{capital\ cost}+\underbrace{C_{iv}^{p}(x_v)}_{port\ cost}+\underbrace{C_{ijv}^{s}(x_v,y_v,z_v)+C_{ijv}^{w}(x_v,y_v,z_v)}_{toll\ cost}\right) \tag{1}$$

Eq. (1) is the objective function of minimizing the fuel cost, capital cost, port cost, and toll cost for all the vessels. The detailed process for each cost is shown in Appendix A.

S.T.:

3.4.1. Logical constraints

The following logical constraints are adopted to determine the shipping company's ability to transport cargo between Asia and Europe.

$$\sum_{v\in V}\sum_{j\in P} x_{ijv} = 1 \quad \forall i \in D_l \tag{2}$$

$$\sum_{v\in V}\sum_{i\in P} x_{ijv} = 1 \quad \forall j \in D_u \tag{3}$$

$$\sum_{j\in D_l\cup o(v)} x_{o(v)jv} = 1 \quad \forall v \in V \tag{4}$$

Table 1
A small case of sets.

Sets	Label				
Vessels (V)	1,2,3				
Cargos (N)	1,2,3,4,5				
Loading ports (D_l)	1(Tianjin)	2(Busan)	3 (Murmansk)	4(Kotka)	5(Shanghai)
Unloading ports (D_u)	6 (Murmansk)	7(Varberg)	8 (Dalian)	9 (Qingdao)	10 (Murmansk)
Initial ports for vessels $o(v)$	2(Busan)	4(Kotka)	5(Shanghai)		
Asian ports (P^A)	1(Tianjin)	2(Busan)	5(Shanghai)	8 (Dalian)	9 (Qingdao)
European ports (P^E)	3 (Murmansk)	4(Kotka)	6 (Murmansk)	7(Varberg)	10 (Murmansk)

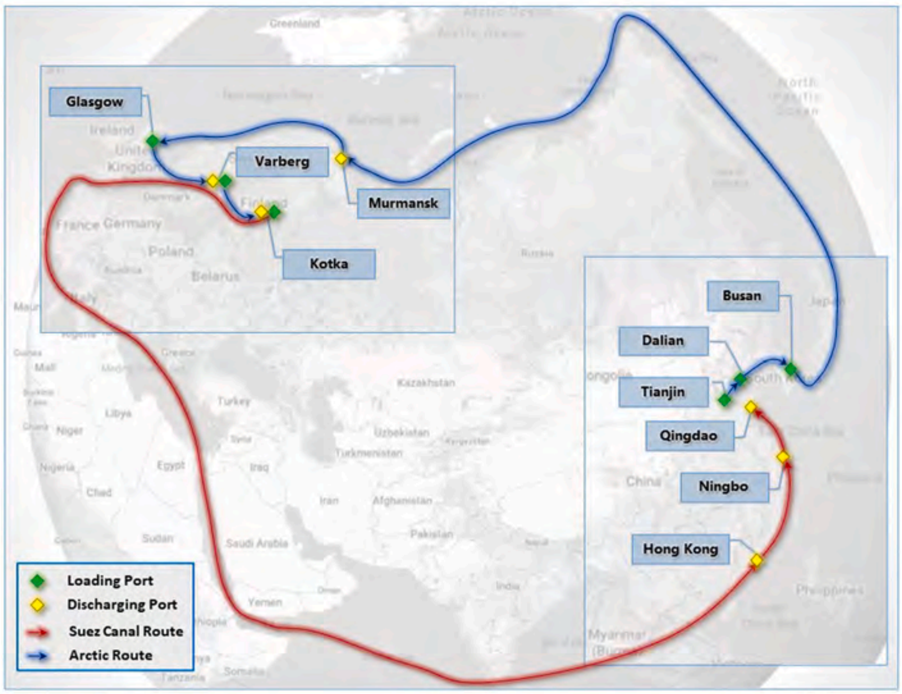

Fig. 1. One vessel schedule plan with the optional route.

$$\sum_{i\in P} x_{iiv} = 0 \quad \forall v \in V \tag{5}$$

$$\sum_{j\in D_l} x_{o(v)jv} = \sum_{j\in D_u} I_{jv} \quad \forall v \in V \tag{6}$$

$$\sum_{i\in D} x_{io(v)v} = 1 \quad \forall v \in V \tag{7}$$

$$\sum_{i\in P} x_{ijv} = \sum_{i\in P} x_{jiv} \quad \forall v \in V, j \in D_l \tag{8}$$

$$\sum_{i\in D} x_{ijv} = \sum_{i\in D} x_{jiv} + I_{jv} \quad \forall v \in V, j \in D_u \tag{9}$$

$$\sum_{j\epsilon D} x_{ijv} - \sum_{j\epsilon D} x_{j(n+i)v} = 0 \quad \forall v \in V, i \in D_l \tag{10}$$

$$u_{iv} + x_{ijv} \le u_{jv} + (2n + N - 1)(1 - x_{ijv}) \quad \forall v \in V, i \in P, j \in D \tag{11}$$

Constraints (2)–(11) are logical Constraints. Among them, Constraints (2)–(3) ensure that all cargo under the contract of contracting must be transported. Constraint (4) ensures that vessels will depart from their initial position. Constraint (5) ensures that vessels cannot access the same port consecutively. Constraint (6) assures that if a vessel starts the route at the initial position, exactly one unloading port will be the last destination on the route. Constraint (7) ensures that vessels will not return to their initial positions. Constraint (8) ensures that if a vessel v arrives at a loading port i, this vessel must leave this port. Constraint (9) ensures that if a vessel v arrives at an unloading port i, this vessel must leave this port or, then, this port will be the last destination on the route. Constraint (10) ensures that the operation plan of the vessel is consistent at the loading port and the unloading port attached to the same cargo. Constraint (11) is the subtour-elimination constraint.

3.4.2. Cargo volume constraints

To ensure a vessel fulfills the requirements of transporting cargo between OD ports, we propose the following cargo volume constraints:

$$x_{ijv}\left(l_{iv} + q_{ji'v} - l_{jv}\right) = 0 \quad \forall v \in V, i, i' \in D, j \in D_l \tag{12}$$

$$x_{i(n+j)v}\left(l_{iv} - q_{ji'v} - l_{(n+j)v}\right) = 0 \quad \forall v \in V, i, i' \in D, j \in D_l \tag{13}$$

$$q_{ijv} = q_i \bullet x_{ijv} \quad \forall v \in V, i \in D_l, j \in D \tag{14}$$

$$q_{ijv} \le l_{iv} \le V^{cap} \quad \forall v \in V, i \in D_l, j \in D \tag{15}$$

Constraints (12)–(13) restrict the relation vessel between the vessel's navigation route and the cargo volume loaded or unloaded by the vessel at the port. This means that the vessel needs to be loaded at the port of loading and unloaded at the corresponding port of unloading. Constraints (14)–(15) are vessel cargo capacity constraints.

3.4.3. Time constraints

To meet the vessel sailing time and time window requirements, we propose the following time constraints:

$$x_{ijv}\left(t_{iv}+d_{ij}(x_v,z_v)\,/\,24s-t_{jv}\right)=0 \quad \forall v\in V,(i,j)\in A \tag{16}$$

$$t_{iv}\leq t_{(n+i)v} \quad \forall v\in V,i\in D_l \tag{17}$$

$$ET_i\leq t_{iv}\leq LT_i \quad \forall v\in V,i\in P \tag{18}$$

Constraint (16) ensures the consistency of the vessel's navigation route and navigation time. Constraint (17) ensures that the vessel arrives at the loading port before the unloading port. Constraint (18) is the time window constraint of cargo.

3.4.4. Decision variable

The following are decision variables that need to be determined by a shipping company.

$$y_v\in\{0,1\} \quad \forall v\in V \tag{19}$$

$$z_{ij}^{AE}\in\{0,1\} \quad \forall i\in P^A,j\in P^E \tag{20}$$

$$z_{ij}^{EA}\in\{0,1\} \quad \forall i\in P^E,j\in P^A \tag{21}$$

$$x_{ijv}\in\{0,1\} \quad \forall v\in V,(i,j)\in A \tag{22}$$

$$I_{iv}\in\{0,1\} \quad \forall v\in V,i\in D_u \tag{23}$$

The above model is a nonlinear integer programming model. To solve the above model, linearization should be made, which is discussed in Appendix B.

4. Case study

This section validates the accuracy of the mathematical model proposed in Section 3 through a case study. The case study takes the perspective of a shipping company and utilizes the dry bulk ship transportation data from 2013 to 2021 on the Arctic route. Correspondingly, the Asian port cities are Shanghai, Ningbo, Dalian, Qingdao, Tianjin, Hong Kong, Busan, Lanshan, and Caofeidian, and the European port cities are Murmansk, Kotka, Varberg, Rotterdam, and Glasgow. By conducting calculations, it explores whether it is economically viable for the shipping company to self-build vessels with ice-breaking ability when the Arctic route allows year-round navigation.

The specific optimization process is as follows: First, we utilize the linearized mathematical model from Appendix B. Then, we incorporate specific parameter data from the case, such as cargo information, vessel parameters, ice-breaking class of VIAs, and one-time channel tolls, into the mathematical model as described in Section 4.2. Finally, we use the CPLEX solver to obtain the optimized solution for the shipping company's irregular vessel operations, including the specific scheduling plan and the optimal decision regarding the need for self-owned VIAs.

4.1. Model solution

The vessel scheduling optimization model studied in this paper is an integer nonlinear programming model with nonlinear factors. After linearizing the model in section 3.16, a solver can be used to solve it. The IBM ILOG CPLEX version 22.1.0 solver is adopted in this paper, with the following computational environment:

Platform: an AMD Ryzen 7 5700G with Radeon Graphics processor, 3.8 GHz clock frequency, and 16 GB RAM available.

Operating system: Windows(R) 10 Professional OS.

The following experiments are conducted by using the default parameter setting of the CPLEX.

4.2. Parameter setting

4.2.1. Cargo information

The primary focus of this paper is to analyze the inclusion of the Northern Sea Route (NSR) in the scheduling of tramp ships between Asia and Europe. Currently, the international bulk market primarily centers around the Pacific route, resulting in relatively lower demand for Asian and European transportation. However, considering the potential of the Arctic route and the expressed intentions of both companies and governments to develop an all-weather Arctic route, we have consolidated the information on bulk vessels transported via the Arctic route from 2013 to 2021(From Center for High North Logistics) and the information on cargoes transported by a shipping company between Asia and Europe in 2020. In this way, more OD cargo data was obtained for calculations based on real cargo data to verify the validity of the model. The relevant cargo information is shown in Table 2. Correspondingly, the Asian port cities are Shanghai, Ningbo, Dalian, Qingdao, Tianjin, Hong Kong, Busan, Lanshan, and Caofeidian, and the European port cities are Murmansk, Kotka, Varberg, Rotterdam, and Glasgow. (For shipping companies, there is a large difference in the cost of shipping via NSR in summer versus winter, in this paper, all bills of cargo are divided equally between summer-autumn and winter-spring for a year, we agree that the starting day of summer is the first day of the year, so that summer and autumn are the first 183 days of the year, and accordingly, winter and spring are the 183rd - 365th days, the specific time window for each shipment is given randomly):

Assume that a shipping company uses 3 vessels to complete the transportation of the above cargo and the initial ports of each vessel are Kotka, Murmansk, and Shanghai.

4.2.2. Vessel parameters

The relevant parameters of the vessels are as follows:

Vessel type: To ensure navigation safety, vessels without ice-breaking capability require ice-breaking pilotage to cross the Arctic route. Russia completed sea tests of its latest VIA Arktika in 2020 and put it into service at the end of the year. Arktika's installed nuclear engine has a shaft power of 60 MW and a typical width of 34 m, making it the largest VIA currently in service (Port News, 2020). The type width of bulk cargo vessels selected in this paper should be less than 34 m to meet the conditions of ice-breaking pilotage. Considering the economy of scale of vessel capacity, we choose COSCO Panamax Type 82,000 tons Kamsa bulk carrier. The length of the vessel is 229.00 m. The width of the type is 32.26 m and the depth of the type is 20.05 m, respectively. The delivery price is about 27 million US dollars.

Vessel capital cost: The delivery price of the Kamsa bulk carrier is \$27 million, assuming a 10-year vessel life and the capital cost of \$2.7 million per year based on straight-line depreciation.

The relevant parameters of the vessel are shown in Table 3.

4.2.3. Ice-breaking class of VIAs

Russia divides the sea ice prediction area of the Northeast Arctic Channel into seven areas according to geographic longitude, as shown in Fig. 2.

According to the Northern Sea Route Administration (http://www.nsra.ru/), the extent of sea ice in July–August 2021 in the Arctic seas is expected to be 20%–24% lower than the 1970–2010 average. The sea ice area in East Siberia and Chukchi is estimated to be 11%–13% and 2%–11% lower than the average (ditto above), respectively. The ice conditions in the whole Arctic seas are expected to be light, and there will be no intermediate or heavy ice situation (As shown in Fig. 3).

From September to November 2021, sea ice formation in each region was 5–12 days later than the average multi-year sea ice formation (1970–2010), with sea ice formation in the De Long Strait (connecting the East Siberian Sea with the Chukchi Sea) and the Chukchi coast expected to be 25 days later than the average. The sea ice conditions of all Arctic seas in autumn 2021 are shown in Fig. 4: The sea ice grades of the

Table 2
Information about transportation demand.

	ID	Loading port	Unloading port	Quantity (ton)	ET of Loading Port (day)	LT of Loading Port (day)	ET of Unloading Port (day)	LT of Unloading Port (day)
Transport of cargo in summer-autumn	1	Kotka	Qingdao	30042	0	5	20	45
	2	Murmansk	Dalian	74849	45	50	65	90
	3	Shanghai	Varberg	12716	75	80	95	120
	4	Tianjin	Murmansk	80959	20	25	40	65
	5	Murmansk	Caofeidian	71786	70	75	90	115
	6	Murmansk	Dalian	79452	20	25	40	65
	7	Hong Kong	Murmansk	74300	40	45	60	85
	8	Shanghai	Murmansk	81216	0	5	20	45
	9	Murmansk	Tainjin	81600	0	5	20	45
	10	Ningbo	Murmansk	56348	45	50	65	90
	11	Shanghai	Glasgow	13514	75	80	95	120
Transport of cargo in winter-spring	12	Murmansk	Qingdao	70202	183	188	203	228
	13	Varberg	Busan	17070	260	265	280	305
	14	Murmansk	Ningbo	44218	290	295	310	335
	15	Dalian	Murmansk	66291	220	225	240	265
	16	Murmansk	Lanshan	41070	255	260	275	305
	17	Caofeidian	Murmansk	81216	305	310	325	350
	18	Murmansk	Shanghai	67520	215	220	235	260
	19	Murmansk	Lanshan	74300	260	265	280	305
	20	Dalian	Murmansk	74849	255	260	275	300
	21	Tianjin	Murmansk	81600	183	188	203	228
	22	Murmansk	Ningbo	56348	183	188	203	228
	23	Qinhuangdao	Rotterdam	25152	220	225	240	265

Source: http://www.nsra.ru/

Table 3
Relevant parameters of vessels.

	DWT (tonnes)	LOA (m)	Draught (m)	Beam (m)	SCNT (tonnage)	Capital Cost ($ million)
Panamax	82000	229	14.45	32.26	27847	27

Barents Sea, Laptev Sea, East Siberian Sea, and Chukchi Sea are light. The ice level in the Kara Sea is intermediate, and the ice level in the northeast Kara Sea is also light. There is no heavy ice condition in the whole Arctic Sea area.

According to Table 4, when the ice condition of 7 regions in the NSR is light, and the ice condition of the Kara Sea and Chukchi Sea is light or intermediate, Arc4 ice-resistant vessels can navigate freely and independently in 7 regions, while when the ice conditions are heavy, ice-breaking pilot vessels are required for piloting. According to Figs. 3 and 4, the ice conditions in seven regions of the NSR in the summer of 2021 are all light, while the ice conditions in the autumn of the NSR are intermediate only in the Kara Sea. It can be concluded that the ARC4-class VIA can freely pass through the NSR in the summer and autumn of 2021. As global warming accelerates the melting of Arctic seas, it is believed that ARC4-class VIAs will still be able to pass NSR freely in summer and autumn after 2021. Therefore, the ice level of the VIA in this paper is set as Arc4.

4.2.4. Channel tolls

Suez Canal Toll: The Suez Canal Toll depends on the type of vessel, route direction (southbound or northbound), Suez Canal Net Tonnage (SCNT), vessel loading or ballast, draft, and width, and is determined by the Special Drawing Right (SDR) rate of the International Monetary Fund. According to the relevant regulations of the Suez Canal Authority, from May 1, 2022, the transit costs of all kinds of vessels (excluding cruise vessels and LNG vessels) passing through the Suez Canal will increase by 10%. Based on known vessel-related parameters, use the online calculator provided by the Left organization to calculate the Suez Canal toll for vessels, which is 227064USD (http://lethagencies.com/).

Vessel ice-breaking pilotage cost: Since 2012, it is no longer mandatory to use VIA for pilotage through the Arctic route. However, due to the change in ice conditions and maritime safety concerns, this paper still assumes that bulk carriers without ice-breaking capability need ice-breaking pilotage (Theocharis et al., 2019). According to the tariff regulations of the Northern Sea Route Authority (NSRA), the ice-breaking pilotage fee is related to the navigation season, the vessel's ice class, the vessel's gross tonnage, and the convoy area. The ice-breaking pilotage fee of Panamax bulk carrier (44163 GT) is calculated

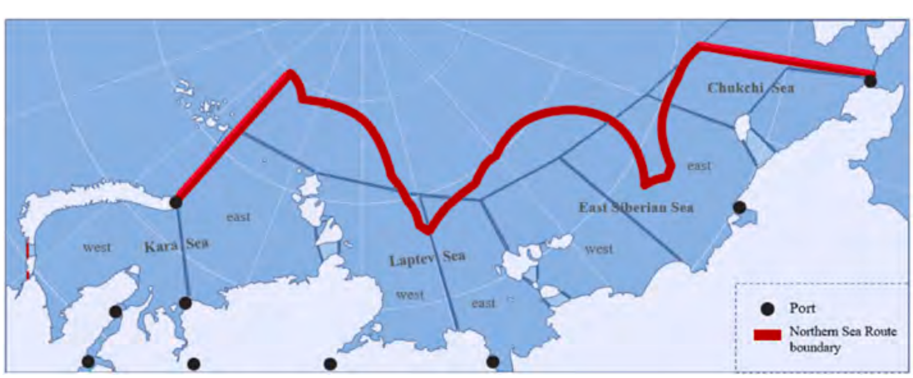

Fig. 2. The seven areas of the Northern Arctic Channel.

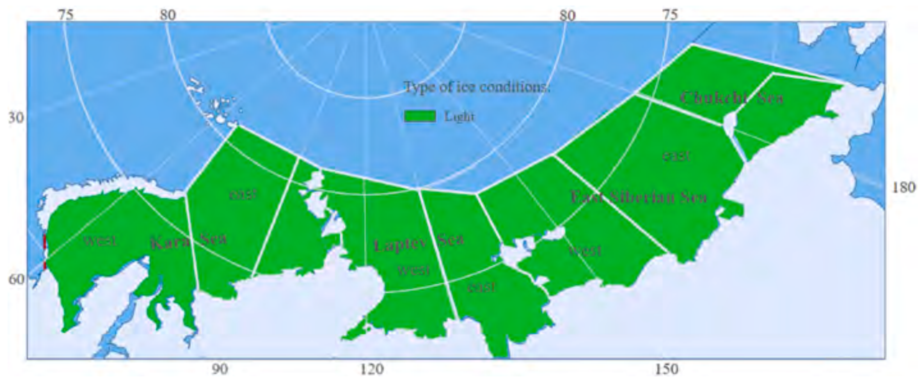

Fig. 3. The ice conditions in the whole Arctic seas in July–Aug 2021.

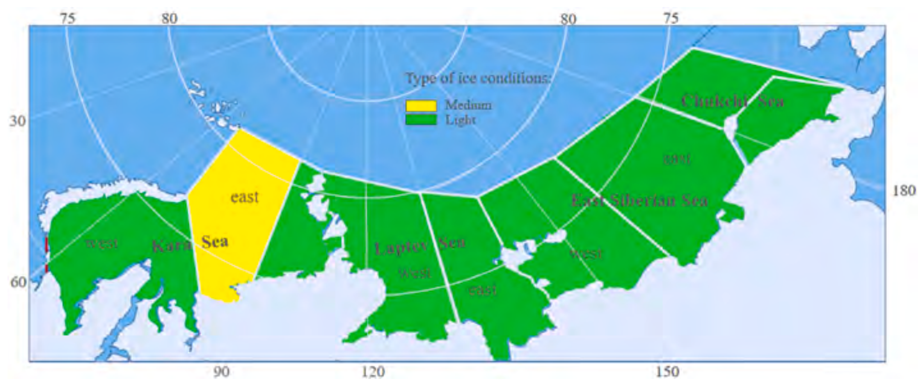

Fig. 4. The ice conditions in the whole Arctic seas in Sep.–Nov. 2021.

Table 4
Allowed navigation zones of Arc4 vessels in the context of ice conditions.

Zone	Ice Condition				
	Independent Navigation		Navigation with VIA		
Kara Sea, west	Medium	Light	Heavy	Medium	Light
Kara Sea, east	Medium	Light	Heavy	Medium	Light
Laptev Sea, west	/	Light	/	Medium	Light
Laptev Sea, east	/	Light	/	Medium	Light
East Siberian Sea, west	/	Light	/	Medium	Light
East Siberian Sea, east	/	Light	/	Medium	Light
Chukchi Sea	Medium	Light	/	Medium	Light

Source: Center for High North Logistics, NSR Information Office, Norway-Murmansk, Russia

by NSRA as 39833931Rub According to the USD/Rub exchange rate of 81.55 in June 2023, the ice-breaking pilotage fee of the vessel through NSR is 488460 USD (http://www.nsra.ru/en/contact.html).

In winter, due to the high thickness and concentration of sea ice, Arc4 class vessels need to be piloted by VIAs to ensure navigation safety. The ice-breaking pilotage fee of the Arc4 VIA is calculated by NSRA calculated as 49792822 Rub. According to the USD/Rub exchange rate of 81.55 in June 2023, the ice-breaking pilotage fee of the vessel through NSR is 610580 USD. The NSRA calculator does not provide a calculation for the ice-breaking pilotage fee of ordinary vessel in winter, indicating that ordinary vessels transit the NSR is currently not possible in winter, so we set the ice-breaking pilotage fee of ordinary vessel to an extreme value *M*.

The relevant channel tolls of the vessel are shown in Table 5.

Table 5
Related channel tolls.

The Arctic Route (USD)				The Suze Canal Route (USD)
VIA		Ordinary vessel		227064
Summer	Winter	Summer	Winter	
0	610580	488460	*M*	

4.2.5. Other related parameters

Vessel Speed: According to the regression calculation by (Wang et al., 2020), the optimal speed of Arctic ice class 4 vessels in 2020 for autonomous driving (piloting without VIAs) on the Arctic route is 13.87–14.24 knots, in this paper, the speed is set to 14 knots and the speed of vessels on the Suez route is also set at 14 knots.

VIA building coefficient: compared with ordinary vessels, the capital cost of ice-breaking vessels requires a certain premium. The premium is directly related to the grade of ice-class vessels. Concerning the premium table of ice class vessels' capital cost by (Wang et al., 2020), the premium of ice class vessels of Arc4 is 19.2% of ordinary vessels, Hence, the VIA building coefficient β is 1.192.

Fuel oil price: According to the regulations of the International Maritime Organization (IMO) in 2020, from January 1, 2020, the maximum sulfur content in vessel fuels other than ECAs will be significantly reduced from 3.5% to 0.5% m/m (mass by mass) (Wang et al., 2021). Therefore, this paper uses very low sulfur fuel oil (VLSFO) to calculate. According to the average cost of 20 ports in the world in April 2023, we set the price of VLSFO as 621 USD per ton based on the current price in the Singapore market. (https://vesselandbunker.com/).

The input parameters are shown in Table 6.

4.3. Result analysis

The findings of this study indicate that to minimize the cost of cargo transportation between all OD ports, the shipping company should establish a total of two vessels with VIA functionality and one ordinary

Table 6
Related input parameters.

Vessel Ice Class	Speed (knots)	Fuel Price (USD)	Capital Cost (million USD)	
Arc4	14	VLSFO	VIA	Ordinary vessel
		621	32.184	27.000

vessel. This underscores the necessity for shipping companies to invest in VIA vessels to align with the emerging trend of year-round navigation on the Arctic route.

To further validate the credibility of these results, the paper calculates and compares the costs incurred by the shipping company when using three ordinary vessels to complete the OD cargo transportation. The comparison is presented in Table 7. The results demonstrate that the cost savings achieved through the construction of VIA vessels, considering the fuel cost and toll cost reductions resulting from the distance advantage of the Arctic route, far outweigh the increased capital costs for the shipping company. This further reinforces the feasibility and practicality of constructing VIA vessels for shipping companies.

Figs. 5–7 show the transport routes for each of the vessels shown. In particular, Fig. 5 shows the transport routes for the ordinary vessel, while Figs. 6 and 7 show the transport routes for the two ice-breakers. As can be seen from Fig. 5, the ordinary vessel chooses the Suez route for navigation throughout the year, indicating that currently, despite the summer season, it is still not economical for the ordinary vessel to pass through the Arctic route due to high pilotage costs, the distance advantage of the Arctic route is not outstanding. As can be seen in Figs. 6 and 7, VIAs are well placed to combine SCR and NSR routes for traffic throughout the year to achieve the objective of minimizing total costs.

Figs. 8–10 correspond to Figs. 5–7 respectively, indicating the time of arrival and idleness of each ship in each port throughout the year. Of these, the results in Fig. 8 provide a good illustration of the reasons why the shipping company builds its own two VIAs instead of three. As can be seen in Fig. 8, due to the more obvious navigational advantage of VIAs in the summer months, Vessel 1 only carried 2 bills of cargo during the summer months, clearly failing to create economies of scale, i.e. the navigational advantage of completing 2 bills of cargoes via NSR failed to compensate for the capital increase brought about by the construction of VIAs. From Figs. 9 and 10, it is evident that during the summer months, selecting the NSR for transportation is undoubtedly the optimal choice for VIA vessels. This is due to the navigational advantages offered by the NSR, as well as the reduced toll costs associated with VIA vessels. Conversely, during the winter season, to avoid the high costs associated with ice-breaking navigation, VIA vessels should opt for the SCR for transportation. This aligns with the findings of the study, which recommend SCR as the preferred route for VIA vessels during winter months.

In conclusion, the marginal benefits brought by shipping companies building their VIAs and choosing NSR for transportation are higher than the increased marginal costs of building the ships. As a result, it is indeed feasible and advantageous for shipping companies to invest in the construction of their VIA vessels.

Table 7
Operating costs for shipping company building and not building VIAs.

Ship form		Total Costs (million USD)				
		Fuel Cost	Port Cost	Toll Cost	Capital Cost	Total Cost
VIA + Ordinary vessel	2 + 1	12.26	0.25	2.95	9.14	24.60
	0 + 3	14.04	0.25	4.54	8.10	26.93

4.4. Sensitivity analysis

The economic viability of constructing a VIA vessel for a shipping company can be determined theoretically by assessing whether the economic benefits derived from the VIA vessel outweigh the associated increased capital costs i.e. whether the savings in ice-breaking pilotage and fuel costs of the VIA through the NSR exceed the increased capital costs. To this end, a sensitivity analysis was conducted on the cost of ice-breaking pilotage for NSR and fuel price.

4.4.1. Sensitivity analysis on ice-breaking pilotage fee

We analyzed the sensitivity of the ice-breaking pilotage fee at $\theta = 0.3–1.8$, where the coefficient θ represents an increase or decrease in the original pilotage fee. The results are shown in Table 8. When $\theta \leq 0.6$, the lower ice-breaking pilotage fee is attractive to shipping companies, all vessels choose the Arctic route all year, except for ordinary vessels that cannot navigate the NSR in the winter; when θ is increased to 0.9 times the current level, in the summer, the navigation fee for the Northern Sea Route (NSR) remains competitive, and ordinary vessels continue to choose the NSR due to its cost advantages. However, during the winter, the cost advantage of the NSR is diminished, and all vessels opt for the Southern Sea Route (SCR) instead; If the ice-breaking pilotage fee is equal to or greater than the prevailing fee, even in the summer, all ordinary vessels choose the SCR route. The high ice-breaking fee renders the NSR economically uncompetitive in such scenarios.

In addition, observing Table 8, it is easy to find that as the NSR ice-breaking pilotage fee changes, the shipping company always chooses to build 2 VIAs, which may be because when the ice-breaking pilotage fee is high, the VIAs have a higher cost advantage in the summer, and the opposite is true in the winter; when the ice-breaking pilotage fee is low, the VIAs have a higher cost advantage in the winter and the opposite in the summer; therefore, the shipping company chooses the optimal shipbuilding option.

4.4.2. Sensitivity analysis on fuel price

The distance advantage of NSR is mainly in fuel cost, and there is a close link between whether a vessel chooses NSR and fuel price. We analyzed the sensitivity to fuel price at $\eta = 0.3–1.8$, where the coefficient η indicates an increase or decrease from the original cost. The results are shown in Table 9. When $\eta \leq 0.9$, the smaller fuel price makes the distance advantage of the NSR not significant, all vessels choose SCR for transport all year, except for VIAs that choose NSR in the summer to be exempted from tolls; when $\eta = 1.2$, the fuel price gives NSR a distance advantage in the summer, and all vessels choose NSR in the summer; when $\eta \geq 1.5$, the distance advantage of NSR becomes more and more obvious, and all vessels choose NSR even in the winter, the cause of this result may be that the distance advantage of NSR due to the higher fuel price compensates for its high ice-breaking pilotage cost in winter.

In addition, with the change of NSR ice-breaking pilotage fee, shipping companies always choose to build 2 ice-breaking ships, which may be because when the fuel price is low, the distance advantage of NSR is not prominent, and building 2 ice-breaking ships at this time indicates that the toll cost plays a key role; when the fuel price is high, the distance advantage of NSR is more and more prominent, but the shipping companies still choose to build 2 ships, which may be due to the third ship carries less cargo (only 1 bill in summer and 2 bills in winter) and the NSR pilotage fee in winter is high, the saving of the fuel cost fails to form a benefit of scale.

5. Conclusions

In conclusion, this paper has focused on the inter-Asia-Europe tramp bulk cargo transportation market and has explored the optimal ship scheduling scheme by effectively utilizing the Arctic route and the Suez Canal route. By adopting a shipping company's perspective and employing a non-linear integer programming model, we aimed to

Fig. 5. The vessel 1 transportation scheduling program between Asia and Europe.

Fig. 6. The vessel 2 transportation scheduling program between Asia and Europe.

minimize overall shipping costs while meeting the cargo transportation needs of shippers. Furthermore, we investigated the economic implications of constructing self-built VIA vessels and examined whether it is necessary for shipping companies to invest in such vessels.

Based on our findings, it is evident that as the cargo volume in Arctic navigation gradually increases, it becomes increasingly advantageous for shipping companies to build VIA vessels. This allows them to achieve economies of scale and realize cost savings. Additionally, considering the rise in fuel prices, the distance advantage offered by the NSR becomes even more appealing, further incentivizing shipping companies to invest in VIA vessels. In summary, this study contributes to the understanding of ship route selection and scheduling decisions in the inter-Asia-Europe tramp bulk cargo transportation market. By considering the economic implications and benefits of VIA vessel construction, we provide valuable insights for shipping companies seeking to optimize their operations in a scenario where the Arctic route remains open year-round.

6. Discussion

Compared with existing studies, this paper considers the issue of ship route selection for the combined NSR/SCR transport while optimizing the scheduling of ordinary vessels between Asia and Europe, and explores whether VIAs should be built to save costs from the perspective of the shipping companies, which fills the gap in the scheduling of tramp ships for the existing NSR transport.

There are some shortcomings in the research of this paper, such as not considering the idle cost of vessels. Since the shipping companies studied in this paper are all self-built vessels, considering their vessel construction costs, the ship idling costs may account for part of the shipping costs while fulfilling the cargo transport needs of the cargo owners, and this factor can be further considered in the subsequent studies. In addition, this paper treats the speed of vessels in NSR and SCR uniformly, which may not be reasonable, and this variable can be

Fig. 7. The vessel 3 transportation scheduling program between Asia and Europe.

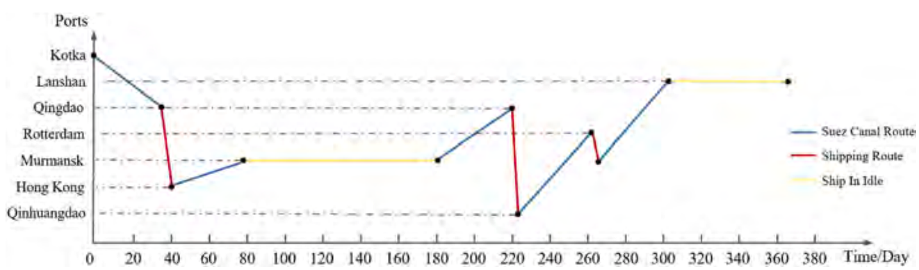

Fig. 8. The time vessel 1 arrived at each port in the transportation scheduling program.

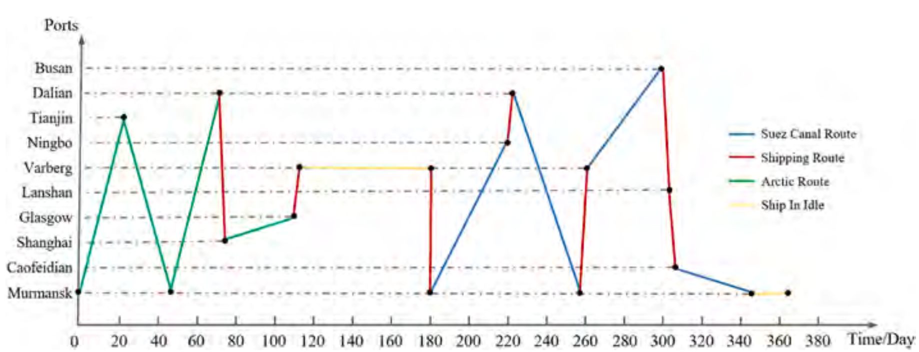

Fig. 9. The time vessel 2 arrived at each port in the transportation scheduling program.

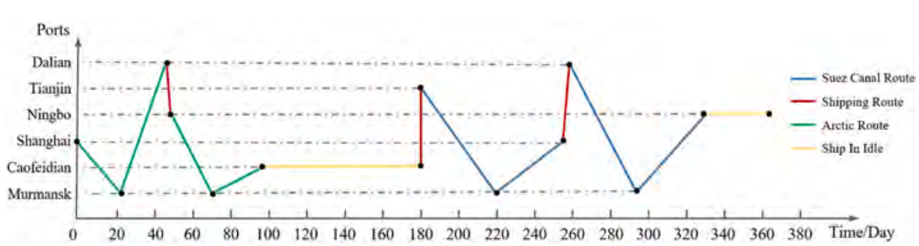

Fig. 10. The time vessel 3 arrived at each port in the transportation scheduling program.

Table 8
Tramp vessel scheduling and costs on different ice-breaking pilotage fee coefficients.

	Total Capital Cost (million USD)	Total Fuel Cost (million USD)	Total Port Cost (million USD)	Total Toll Cost (million USD)	Total Cost (million USD)	Number of VIAs	Number of options for NSR			
							Summer		Winter	
							VIA	Ordinary vessel	VIA	Ordinary vessel
$\theta = 0.3$	9.14	9.19	0.25	2.21	20.78	2	9	1	10	0
$\theta = 0.6$	9.14	9.19	0.25	4.18	22.75	2	9	1	10	0
$\theta = 0.9$	9.14	11.82	0.25	2.94	24.14	2	9	1	0	0
$\theta = 1.2$	9.14	12.26	0.25	2.95	24.60	2	8	0	0	0
$\theta = 1.5$	9.14	12.26	0.25	2.95	24.60	2	8	0	0	0
$\theta = 1.8$	9.14	12.26	0.25	2.95	24.60	2	8	0	0	0

Table 9
Tramp vessel scheduling and costs on different fuel prices.

	Total Capital Cost (million USD)	Total Fuel Cost (million USD)	Total Port Cost (million USD)	Total Toll Cost (million USD)	Total Cost (million USD)	Number of VIAs	Number of options for NSR			
							Summer		Winter	
							VIA	Ordinary vessel	VIA	Ordinary vessel
$\eta = 0.3$	9.14	3.67	0.25	2.95	16.01	2	8	0	0	0
$\eta = 0.6$	9.14	9.85	0.25	2.95	22.18	2	8	0	0	0
$\eta = 0.9$	9.14	11.04	0.25	2.95	23.37	2	8	0	0	0
$\eta = 1.2$	9.14	14.27	0.25	2.99	26.64	2	9	1	0	0
$\eta = 1.5$	9.14	14.06	0.25	6.44	29.88	2	9	1	9	0
$\eta = 1.8$	9.14	16.86	0.25	6.44	32.68	2	9	1	9	0

explored more deeply in the subsequent research work.

Theoretically, whether a shipping company should build VIAs and how many VIAs it should build depends on whether the increased shipbuilding cost per VIA is less than the reduction in tolls and fuel costs. This is not only related to the price of shipbuilding, the NSR's ice-breaking pilotage fee and the price of fuel, but also to the amount of cargo transported by each ship. If the number of cargo bills transported is small, and its cost savings do not result in economies of scale, the construction of VIAs may not be economical. Observing the OD ports of cargoes transported through the Arctic route in the past years, it is not difficult to find that the ports between China and Murmansk of Russia accounted for a large proportion, according to the current world situation, China and Russia are trading more and more frequently, and as the volume of trade cargoes between China and Russia increases, the cost scale advantage of building VIAs will become more obvious, more and more shipping companies will choose to build VIAs to navigate the Arctic route.

In future research, it would be valuable to incorporate the idle cost of vessels, explore more nuanced vessel speeds in different routes, and conduct a comprehensive cost-benefit analysis considering various trade scenarios. By addressing these aspects, we can gain a more accurate understanding of the economic implications and optimize ship scheduling schemes for tramp bulk cargo transportation in the inter-Asia-Europe market.

Funding

This work was supported by the National Natural Science Foundation of China (Grant no. 72201252).

CRediT authorship contribution statement

Chengcheng Liu: Writing – original draft, Visualization, Data curation. **Yanjie Zhou:** Writing – review & editing, Investigation, Conceptualization. **Zhongzhen Yang:** Supervision, Methodology. **Yumin Li:** Supervision, Methodology. **Tao Li:** Writing – original draft.

Declaration of competing interest

The author(s) declared no potential conflicts of interest concerning this article's research, authorship, and/or publication.

Data availability

Data will be made available on request.

Appendix A

Fuel Cost

The fuel is consumed during the sailing period and the daily fuel consumption of each vessel (in tons/day) is given by a function $F(s,k)$, where s (in knots) denotes the vessel's speed and k (in tons) represents payload. In this paper, we use the realistic closed-form approximation of F is given by (Wen et al., 2017).

$$F(s,k) = \mu s^3 (k+w)^{2/3} \tag{24}$$

where μ is a constant and w is the vessel of lightship weight. Let P^f be the fuel price. Therefore, the fuel consumption costs between ports i and j for the vessel is expressed as:

$$C_{ij}^f(x_v, z_v) = P^f \bullet F(s,k) \bullet d_{ij}(x_v, z_v) \, / \, 24s \ \forall (i,j) \in A, v \in V \tag{25}$$

After replacing the $F(s,k)$, the above equation can be expressed as $C_{ij}^f(x_v,z_v) = P^f \bullet \mu s^3 (k+w)^{2/3} \bullet d_{ij}(x_v,z_v)/24s$. In the above equation, $x_v = (x_{ii'v}, x_{jj'v}, \ldots, x_{ijv})$ and $z_v = (z_{ij}^{AE}, \ldots, z_{ij}^{EA})$. x_v is a decision vector for whether vessel v sails from port i to port j. z_v is a decision vector for vessel v for determining whether a vessel chooses the Arctic route or not.

Let $d_{ij}(x_v, z_v)$ be the vessel v sailing distance from ports i and j. x_v and z_v are used to calculate the shipping route of the vessel v. The expression of $d_{ij}(x_v, z_v)$ is defined as follows:

$$\begin{aligned} d_{ij}(x_v, z_v) = &\sum\nolimits_{i,i' \in P^A} d_{ii'}^A x_{ii'v} + \sum\nolimits_{j,j' \in P^E} d_{jj'}^E x_{jj'v} + \sum\nolimits_{i \in P^A, j \in P^E} d_{ij}^{NAE} \bullet z_{ij}^{AE} \bullet x_{ijv} + \sum\nolimits_{i \in P^A, j \in P^E} d_{ij}^{SAE} \bullet \left(1 - z_{ij}^{AE}\right) \bullet x_{ijv} + \sum\nolimits_{i \in P^E, j \in P^A} d_{ij}^{NEA} \bullet z_{ij}^{EA} \bullet x_{ijv} \\ &+ \sum\nolimits_{i \in P^E, j \in P^A} d_{ij}^{SEA} \bullet \left(1 - z_{ij}^{EA}\right) \bullet x_{ijv} \ \forall v \in V \end{aligned} \tag{26}$$

Port Cost

Concerning port charges, we have taken into account one-time charges at the port and the cost of loading and unloading cargo at the port. Let p_i is the lump-sum payment at port i. And w_i is the cost of loading and unloading per ton of cargo at port i, $C_{iv}^p(x_v)$ denotes the port cost of port i for vessel v:

$$C_{iv}^p(x_v) = \sum\nolimits_{(i,j) \in A} x_{ijv} \bullet p_i + \sum\nolimits_{(i \in D_l, j \in D)} x_{ijv} \bullet q_{ijv} \bullet w_i + \sum\nolimits_{(i \in D, j \in D_u)} x_{ijv} \bullet q_{ijv} \bullet w_j \ \forall v \in V \tag{27}$$

Capital Cost

The capital cost of VIAs is higher than that of ordinary vessels, and the premium is directly related to the grade of VIAs. Let β be the VIA building coefficient and $C_v(y_v)$ denotes the capital costs of vessels, including the capital costs for VIAs and ordinary vessels:

$$C_v(y_v) = C^n \bullet (N + (\beta - 1) \bullet y_v) \quad \forall v \in V \tag{28}$$

Toll Cost

The ice-breaking pilotage fee of the Arctic route is related to factors such as the type of vessels and the navigation season, etc. Therefore, the tolls for different types of vessels vary from season to season. Let $C^s_{ijv}(x_v, y_v, z_v)$ denotes the tolls of the vessel v in summer and let $C^w_{ijv}(x_v, y_v, z_v)$ denotes the tolls of the vessel v in winter, including ice-breaking pilotage fees for the Arctic shipping route and Suez Canal tolls, among them, VIAs do not require ice-breaking pilotage fees in summer.

$$C^s_{ijv}(x_v, y_v, z_v) = \left(\sum\nolimits_{i\in P^A, j\in P^E} z^{AE}_{ij} \bullet x_{ijv} + \sum\nolimits_{i\in P^E, j\in P^A} z^{EA}_{ij} \bullet x_{ijv}\right)(1-y_v)C^{tos} + \left[\sum\nolimits_{i\in P^A, j\in P^E}\left(1-z^{AE}_{ij}\right)\bullet x_{ijv} + \sum\nolimits_{i\in P^E, j\in P^A}\left(1-z^{EA}_{ij}\right)\bullet x_{ijv}\right]C^{ts}\ \forall v\in V \tag{29}$$

$$C^w_{ijv}(x_v, y_v, z_v) = \left(\sum\nolimits_{i\in P^A, j\in P^E} z^{AE}_{ij} \bullet x_{ijv} + \sum\nolimits_{i\in P^E, j\in P^A} z^{EA}_{ij} \bullet x_{ijv}\right)\left[y_v C^{tiw} + (1-y_v)C^{tos}\right] + \left[\sum\nolimits_{i\in P^A, j\in P^E}\left(1-z^{AE}_{ij}\right)\bullet x_{ijv} + \sum\nolimits_{i\in P^E, j\in P^A}\left(1-z^{EA}_{ij}\right)\bullet x_{ijv}\right]C^{ts}\ \forall v\in V \tag{30}$$

Appendix B

Model linearization

The optimization model of tramp vessel scheduling in this paper is an integer nonlinear programming model, with complex structure and components, including integer variables, 0–1 variables, and mixed equality and inequality constraints. To solve the problem effectively, linearize all nonlinear factors in the model to transform the model into a mixed integer linear programming problem.

Among them, equations (29) and (30), which are used to solve for the vessel's toll, three decision variables are multiplied, which is a nonlinear function. Therefore, the linearization method of the multiplication of two decision variables is used to linearize the situation. δ_{ijv} and φ_{ijv} are auxiliary variables and $\delta_{ijv} = x_{ijv} \bullet z^{AE}_{ij}$ and $\varphi_{ijv} = x_{ijv} \bullet z^{EA}_{ij}$ which means that $\delta_{ijv}, \varphi_{ijv} \in \{0, 1\}$, Then equations (29) and (30) can be linearized to following constraints:

$$\delta_{ijv} \le x_{ijv}\quad \forall v\in V, i\in P^A, j\in P^E \tag{31}$$

$$\delta_{ijv} \le z^{AE}_{ij}\quad \forall v\in V, i\in P^A, j\in P^E \tag{32}$$

$$\varphi_{ijv} \le x_{ijv}\quad \forall v\in V, i\in P^E, j\in P^A \tag{33}$$

$$\varphi_{ijv} \le z^{EA}_{ij}\quad \forall v\in V, i\in P^E, j\in P^A \tag{34}$$

$$x_{ijv} + z^{AE}_{ij} - 1 \le \delta_{ijv}\ \forall v\in V, i\in P^A, j\in P^E \tag{35}$$

$$x_{ijv} + z^{EA}_{ij} - 1 \le \varphi_{ijv}\ \forall v\in V, i\in P^E, j\in P^A \tag{36}$$

$$C^s_{ijv}(x_v, y_v, z_v) = \left(\sum\nolimits_{i\in P^A, j\in P^E}\delta_{ijv} + \sum\nolimits_{i\in P^E, j\in P^A}\varphi_{ijv}\right)(1-y_v)C^{tos} + \left[\sum\nolimits_{i\in P^A, j\in P^E}\left(x_{ijv}-\delta_{ijv}\right) + \sum\nolimits_{i\in P^E, j\in P^A}\left(x_{ijv}-\varphi_{ijv}\right)\right]C^{ts}\quad \forall v\in V \tag{37}$$

$$C^w_{ijv}(x_v, y_v, z_v) = \left(\sum\nolimits_{i\in P^A, j\in P^E}\delta_{ijv} + \sum\nolimits_{i\in P^E, j\in P^A}\varphi_{ijv}\right)\left[y_v C^{tiw} + (1-y_v)C^{tos}\right] + \left[\left[\sum\nolimits_{i\in P^A, j\in P^E}\left(x_{ijv}-\delta_{ijv}\right) + \sum\nolimits_{i\in P^E, j\in P^A}\left(x_{ijv}-\varphi_{ijv}\right)\right]\bullet x_{ijv}\right]C^{ts}\ \forall v\in V \tag{38}$$

Cargo volume constraints (12)–(13) have a nonlinear factor of multiplying 0–1 variable by integer variable. The "Big-M" method is adopted to transform the nonlinear function into a linear function. The constraints (12)–(13) could be replaced by the following inequations.

$$l_{jv} \ge l_{iv} + q_{ji'v} - M\left(1-x_{ijv}\right)\quad \forall v\in V, i, i'\in D, j\in D_l \tag{39}$$

$$l_{(n+j)v} \ge l_{iv} - q_{ji'v} - M\left(1-x_{i(n+j)v}\right)\quad \forall v\in V, i, i'\in D, j\in D_l \tag{40}$$

Linearization of time constraint (16) is also adopted by the "Big-M" method. Constraint (16) could be replaced by the following inequation.

$$t_{jv} \ge t_{iv} + d_{ij}(x_v, z_v)/24s - M\left(1-x_{ijv}\right)\quad \forall v\in V, (i,j)\in A \tag{41}$$

The Linear Mathematical Model

$$Min \sum\nolimits_{v\in V}\left(\underbrace{C^f_{ij}(x_v, z_v)}_{fuel\ cost} + \underbrace{C_v(y_v)}_{capital\ cost} + \underbrace{C^p_{iv}(x_v)}_{port\ cost} + \underbrace{C^s_{ijv}(x_v, y_v, z_v) + C^w_{ijv}(x_v, y_v, z_v)}_{toll\ cost}\right) \tag{42}$$

S.T.:

Eq. (2)-Eq. (11), Eq. (14)-Eq. (15), Eq. (17)-Eq. (23), Eq. (31)-Eq. (41).

The above model is the linear model that could be solved by Cplex and other solvers.

Appendix C

Table C.1
Value of correlation parameters

k	The payload of the vessel	82000(t)
w	The vessel of lightship weight	5(t)
β	The VIA building coefficient	1.192
μ	Fuel consumption coefficient of the vessel	5.79×10^{-6}
f	The light fuel consumption of the vessel per day at the port	2 (t/day)

References

Appelgren, L.H., 1969. A column generation algorithm for a ship scheduling problem. Transport. Sci. 3 (1), 53–68. https://doi.org/10.1287/trsc.3.1.53.

Castillo-Villar, K.K., et al., 2014. A heuristic procedure for a ship routing and scheduling problem with variable speed and discretized time windows. Math. Probl Eng. 2014, 750232 https://doi.org/10.1155/2014/750232.

De Armas, J., et al., 2015. A hybrid GRASP-VNS for ship routing and scheduling problem with discretize-d time windows. Eng. Appl. Artif. Intell. 45, 350–360. https://doi.org/10.1016/j.engappai.2015.07.013.

Dmitrenko, A., et al., 2022. Peculiarities of ice breaker ships' use on the Northern Sea Route, taking into account seasonality. In: Manakov, A., Edigarian, A. (Eds.), International Scientific Siberian Transport Forum TransSiberia - 2021, Lecture Notes in Networks and Systems, vol. 402. Springer, Cham. https://doi.org/10.1007/978-3-030-96380-4_108.

Furuichi, M., Otsuka, N., 2015. Proposing a common platform of shipping cost analysis of the Northern Sea Route and the Suez canal route. Marit. Econ. Logist. 17 (1), 9–31. https://doi.org/10.1057/mel.2014.29.

Faury, O., et al., 2020. Best maritime transportation option for the Arctic crude oil: a profit decision model. Transport. Res. E Logist. Transport. Rev. 136, 101865 https://doi.org/10.1016/j.tre.2020.101865.

Fan, H., et al., 2021. Heterogeneous tramp ship scheduling and speed optimization with fuzzy time window. J. Shanghai Jiao Tong Univ. (Sci.) 55 (3), 297–310.

Han, C.H., 2011. Economic feasibility on the Northern Sea Route: the case of container shipping. J. Ship. Logist. 27 (4), 583–605. https://doi.org/10.1016/j.ijpe.2009.03.018.

Han, J., 2020. Russia's arctic icebreaker infrastructure project by 2035: necessities, current situation. Eval. Kor. J. Siber. Stud. 24 (2), 1–35. https://doi.org/10.22892/KSC.2020.24.2.01.

Liu, M., Kronbak, J., 2010. The potential economic viability of using the Northern Sea Route (NSR) as an alternative route between Asia and Europe. J. Transport Geogr. 18 (3), 434–444. https://doi.org/10.1016/j.jtrangeo.2009.08.004.

Lee, S.M., et al., 2018. Method for a simultaneous determination of the path and the speed for ship route planning problems. Ocean Eng. 157, 301–312. https://doi.org/10.1016/j.oceaneng.2018.03.068.

Li, M., et al., 2020. Analyzing the impact of the Northern Sea Route on tramp ship routing with uncertain cargo availability. In: 11th International Conference on Computational Logistics (ICCL). Electr Network, pp. 68–83.

Liu, C., et al., 2021. Comparing the minimal costs of Arctic container shipping between China and Europe: a network schemes perspective. Transport. Res. E Logist. Transport. Rev. 153, 102423 https://doi.org/10.1016/j.tre.2021.102423.

Lee, H.W., et al., 2021. Ship route planning in Arctic Ocean based on POLARIS. Ocean Eng. 234, 109297 https://doi.org/10.1016/j.oceaneng.2021.109297.

Li, L., et al., 2022. Branch-and-price algorithm for the tramp ship routing and scheduling problem considering ship speed and payload. J. Mar. Sci. Eng. 10 (12), 1811. https://doi.org/10.3390/jmse10121811.

Li, M., et al., 2022. Robust liner ship routing and scheduling schemes under uncertain weather and ocean conditions. Transport. Res. C Emerg. Technol. 137, 103593 https://doi.org/10.1016/j.trc.2022.103593.

Li, M., et al., 2022. Stochastic tramp ship routing with speed optimization: analyzing the impact of the Northern Sea Route on CO2 emissions. Ann. Oper. Res. https://doi.org/10.1007/s10479-022-04923-w.

Meng, Q., et al., 2017. Viability of transarctic shipping routes: a literature review from the navigational and commercial perspectives. Marit. Pol. Manag. 44 (1), 16–41. https://doi.org/10.1080/03088839.2016.1231428.

Milakovic, A.-S., et al., 2018. Current status and future operational models for transit shipping along the Northern Sea Route. Mar. Pol. 94, 53–60. https://doi.org/10.1016/j.marpol.2018.04.027.

Norstad, I., et al., 2011. Tramp ship routing and scheduling with speed optimization. Transport. Res. C Emerg. Technol. 19 (5), 853–865. https://doi.org/10.1016/j.trc.2010.05.00.

Peng, G., et al., 2020. What do global climate models tell us about future Arctic Sea ice coverage changes? Climate 8 (1), 15. https://doi.org/10.3390/cli8010015.

Schoyen, H., Brathen, S., 2011. The Northern Sea Route versus the Suez canal: cases from bulk shippin-g. J. Transport Geogr. 19 (4), 977–983. https://doi.org/10.1016/j.jtrangeo.2011.03.003.

Skripnuk, D.F., et al., 2020. Analysis of the current state of the Northern Sea Route and the potential development of the icebreaker fleet. IOP Conf. Ser. Earth Environ. Sci. 539, 012129 https://doi.org/10.1088/1755-1315/539/1/012129.

Shu, Y.Q., et al., 2023. Path planning for ships assisted by the icebreaker in ice-covered waters in the Northern Sea Route based on optimal control. Ocean Eng. 267, 113182 https://doi.org/10.1016/j.oceaneng.2022.113182.

Tang, L., et al., 2013. Model of tramp ship scheduling with variable speed based on set partition appr-oach. J. Shanghai Jiao Tong Univ. (Sci.) 47 (6), 909–915.

Theocharis, D., et al., 2018. Arctic shipping: a systematic literature review of comparative studies. J. Transport Geogr. 69, 112–128. https://doi.org/10.1016/j.jtrangeo.2018.04.010.

Theocharis, D., et al., 2019. Feasibility of the Northern Sea Route: the role of distance, fuel prices, ice breaking fees and ship size for the product tanker market. Transport. Res. E Logist. Transport. Rev. 129, 111–135. https://doi.org/10.1016/j.tre.2019.07.003.

Wen, M., et al., 2016. Full-shipload tramp ship routing and scheduling with variable speeds. Comput. Oper. Res. 70, 1–8. https://doi.org/10.1016/j.cor.2015.10.002.

Wen, M., et al., 2017. A multiple ship routing and speed optimization problem under time, cost and environmental objectives. Transport. Res. Transport Environ. 52, 303–321. https://doi.org/10.1016/j.trd.2017.03.009.

Wan, Z., et al., 2018. Energy-saving potential and an economic feasibility analysis for an arctic route between Shanghai and Rotterdam: case study from China's largest container sea freight operator. Sustainability 10 (4), 921. https://doi.org/10.3390/su10040921.

Wang, C., Chen, C., 2020. An integrated scheduling model of refueling schemes and speed optimization of consecutive voyages for tramp ships. J. Transport. Syst. Eng. Inform. Technol. 20 (6), 233–239.

Wang, D., et al., 2020. Feasibility of the Northern Sea Route for oil shipping from the economic and environmental perspective and its influence on China's oil imports. Mar. Pol. 118, 104006 https://doi.org/10.1016/j.marpol.2020.104006.

Wang, Y., et al., 2021. Feasibility of the Northeast Passage: the role of vessel speed, route planning, and ice-breaking assistance determined by sea-ice conditions for the container shipping market during 2020-2030. Transport. Res. E Logist. Transport. Rev. 149, 102235 https://doi.org/10.1016/j.tre.2021.102235.

Xu, H., et al., 2018. Economic feasibility of an NSR/SCR-combined container service on the Asia-Europe lane: a new approach dynamically considering sea ice extent. Marit. Pol. Manag. 45 (4), 514–529. https://doi.org/10.1080/03088839.2018.1443521.

Xu, L., Yu, Q., 2022. Performance analysis: using the Northern Sea Route as an alternative to traditional routes. J. Marine Sci. Technol.-Taiwan 30 (6), 352–363. https://doi.org/10.51400/2709-6998.2591.

Yang, A., et al., 2021. An optimization model for tramp ship scheduling considering time window and seaport operation delay factors. J. Adv. Transport. 2021, 6650097 https://doi.org/10.1155/2021/6650097.

Zhang, Y., et al., 2016. Shipping efficiency comparison between Northern Sea Route and the conventional asia-europe shipping route via Suez canal. J. Transport Geogr. 57, 241–249. https://doi.org/10.1016/j.jtrangeo.2016.09.008.

Zhang, C., et al., 2019. Data-driven ship energy efficiency analysis and optimization model for route planning in ice-covered Arctic waters. Ocean Eng. 186, 106071 https://doi.org/10.1016/j.oceaneng.2019.05.053.

Zhang, C., et al., 2022. A three-dimensional ant colony algorithm for multi-objective ice routing of a shi-p in the Arctic area. Ocean Eng. 266 (5), 113241 https://doi.org/10.1016/j.oceaneng.2022.113241.

Zhou, Y., Kim, K.H., 2020a. Optimal parameters in concession contracts between container terminal operators and investors. Int. J. Logist. Res. Appl. 23 (6), 602–625. https://doi.org/10.1080/13675567.2020.1754772.

Zhou, Y., Kim, K.H., 2020b. A game theoretic model and a coevolutionary solution procedure to determine the terminal handling charges for container terminals. Comput. Ind. Eng. 144, 106466 https://doi.org/10.1016/j.cie.2020.106466.