International Journal of Hybrid Information Technology
Vol.9, No.4 (2016), pp. 93-104
http://dx.doi.org/10.14257/ijhit.2016.9.4.09

A Scheduling Model of the Icebreaker Assistance Service in the Northern Sea Route

[1, 2]Yi Ding, [1]Weiwen Zhou, [1]Dongmin Xu and [1]Guolong Lin

[1]Logistics Research Center, Shanghai Maritime University, Shanghai 200135, China;
[2]Antai College of Economics & Management, Shanghai Jiao Tong University, Shanghai 200135, China

Abstract

The melting of the sea ice in the Arctic area increases the possibility of exploiting the Northern Sea Route (NSR)by economic method. Compared to the traditional routes, navigating through the Northern Sea Route (NSR) will save much distance and time from Asia to Europe, but the ice condition along the NSR is a key obstacle to most vessels. To ensure the safety of the navigation, ice breaker assistance service becomes crucial. This paper introduces the procedure of icebreaker assistance service firstly, and then a static scheduling model is presented to illustrate icebreaker assistance service. Considering real operation, a dynamic model is proposed, and First Come First Serve (FCFS) principle is implemented into models. The experiment results show that this model is beneficial to control the average waiting time, while it may leads to wait too long for some vessels. And the average fuel cost of each trip remains stable even increasing service request.

Keywords: *Northern Sea Route; scheduling model; FCFS*

1. Introduction

Nowadays, maritime trade is dominated by North America, Europe and Asia. The Atlantic, the Pacific and the Indian Ocean cover 71% of the global ocean area, and most trades happen in these three oceans [1]. The appearance of the Suez Canal and the Panama Canal provide short cuts between those oceans, and contributed to time saving and economic benefit. The keen competition in maritime industry forces ship owners to find another efficient and economic route.

Due to climate change the melting of sea ice in the Arctic Ocean is possible and has a great impact on the Northern Sea Route (NSR) [2]. More ice-free areas extended ice-free time, which give a chance to the development of NSR. As increasing number of ships going across NSR, some experts realized that the NSR is a potential route in future. Shipping through the NSR could save a lot of distance from Asia (Yokohama) to Europe (Rotterdam) [3], which makes NSR become more important. But a lot of factors limit the development of NSR. Even though the rising of the world temperature extend the duration of ice-free season, navigating through the NSR alone is still not recommended when considering the floating ice [4]. Most of the vessels when entering the NSR area needs icebreaking service provided with Northern Sea Route Administration. Thereby Russia's management and operation of ice-breaking service plays an important role in the development of NSR, and then may influence ship-owners' decision-making.

Ice-breaking ships escort the merchant ships when navigating through this route. The service capability is not only determined by the number of icebreakers but also by the scheduling of service efficiency. This paper will focus on the scheduling of the icebreaker assistance service.

A scheduling covers ship-owners who raise the service request, the central unit the service and the icebreakers. The requests of ship-owners transfers to the central unit first, then the central unit arranges the service according to the origins, destinations and the time limitation. In a static icebreaker assistance model, all requests from the ship-owners transfers to the central unit first, then the central unit arranges the service according to the origins, destinations and the time limitation in the static icebreaker assistance model, the service strategy is determined in advance, whereas the service strategy is adjusted along with the new requests in the dynamic icebreaker assistance model.

Due to the fact that Russia is not willing to develop the route for commercial use, few academic articles discussed about the schedule of icebreakers along the NSR. This paper attempts to do some research in the field of the scheduling the icebreaker assistance service of NSR. And the waiting time and fuel consumption under different circumstances are studied.

2. Background

2.1 The Definition of the NSR

The NSR is a shipping lane officially defined by Russian legislation from the Atlantic Ocean to the Pacific Ocean specifically running along the Russian Arctic coast from Murmansk on the Barents Sea, along Siberia, to the Bering Strait and Far East (seeFig 1). Before the beginning of the 20th century it was called the Northeast Passage, and is still sometimes referred to by that name [5].

Figure 1. Map of NSR. Source: Kazakhstan, Russia

The rapid reduction of the ice cap in the Arctic Ocean in recent years has increased the focus on the possibility of expanding and commercializing Trans-Arctic shipping which would drastically shorten transport times between Europe and Asia and North America. Especially NSR is of significant interest. TraustiValsson and Gudmundur F Ulfarsson (2011) used geospatial maps to interpret what a scenario with a warming Arctic with less ice means for activity structures of the globe in the future [6]. Some experts hold the view that by using the NSR as a substitute route, the transportation cost and transportation time can be decreased, some cities along the NSR will benefit from that route. Granberg（1998）analyze the new policy lunched by the Russian government at the Post-Soviet era and the situation of the NSR, navigate through the NSR will save about 50% of the sailing time than go through the Suez Canal route [7]. Obviously, such kind of research neglect the tough navigation condition along the NSR. Even though the ice-covered area has been reduced, sea ice is still an obstacle to the vessels navigating the NSR. Liu and Kronbak (2010) list the advantage and the factors which limit the development of the NSR, a comparison also made in their research to analyze the competitive of the NSR. The results shows that the NSR is not feasible now [8]. But the statistical date implies that the NSR is becoming more and more popular: in 2010, only four commercial vessels transited the NSR. The number soared to 46 in 2012. In 2013, Russian authorities have issued 71 permits. On an international conference about the Barents Sea, Medvedev said shipping could more than double, while Mikhail Belkin, an adviser at Russian nuclear icebreaker fleet said usage of the route could rise from about 1.24 million tons of cargo in 2012 to 40 million tons by 2021.Hong (2012) discuss the potential opportunities and the challenges that the potential route will bring to China's maritime transportation [9]. Not only China, other far east countries will also benefit from this route, like Japan and Korea.

According to the Rules of Navigation on the Water Area of the Northern Sea Route, Russian government established the order of the organization of navigation of ships in the water area of the Northern Sea Route, rules of the icebreaker assistance in the water area of the Northern Sea Route, rules of the ice pilotage of ships in the water area of the Northern Sea Route. Russia authorized the NSRA to control actual operations along the NSR, including scheduling, route assignment, navigational support, pilotage, etc.

2.2 Ice-breaking Service and Ice-breaking Fee

The ship-owner, the representative of the ship owner or the captain of the ship have to apply the permit from the NSRA for going through the NSR in advance (not less than 15 days prior). The application must contain the data about the applicant, indicating the full name and (if applicable) identification code of the International Maritime Organization (IMO number), etc. [10]. The NSRA will process the application since they receive it, all the available ice-breakers will be taken into consideration and the proper ice breakers will be sent to the ports where the merchant ships stays in.

Russia has the world's largest and most powerful ice-breaker fleet, including 6 active nuclear ice-breakers and several diesel-electric icebreakers. The number of icebreakers (see Fig 2) reached to 37 in 2013. According to Russia's management of the regulation of ice-breakers, only less than 20 icebreakers are available for commercial use right now. At the moment, the number of the icebreakers can cover most needs, but as the demand increased year after year, the number commercial use icebreakers seems small which will result in discontinuity of the service which means the merchant ships have to wait for an available icebreaker.

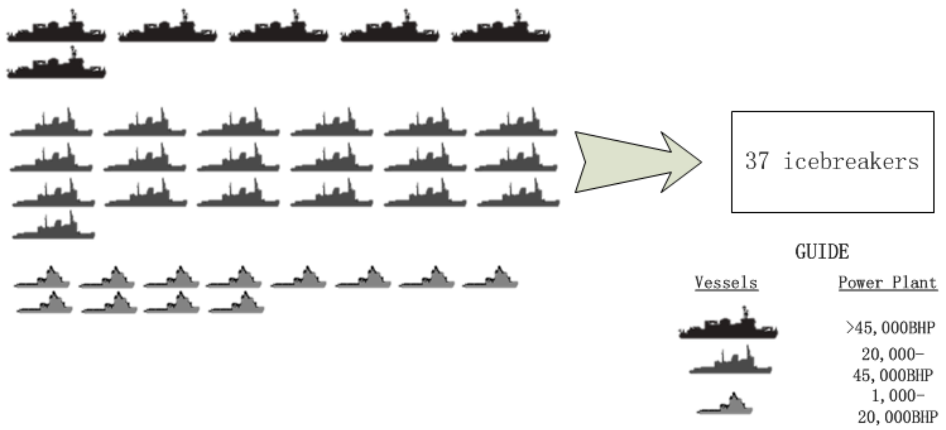


Figure 2. Icebreakers of Russia

Ships owners have to pay service fee (sometimes we call it Russian NSR fees) to NSRA, the Russian NSR fee depends on ship size, ice class, the route and the level of support required. In addition to ice-breaking, this fee includes guiding by reconnaissance aircraft, hydrographic and meteorological services and the use of communication systems. The ice-break fee is a great obstacle to the NSR users because it's almost twice the price of the Suez Canal fee. Since the ice-break fee is always changing, the statistic dates in the table are handled in advance. In 1980s, the ice-break fees were about 3.0 USD/ton while the cargo volumes transported along the NSR were 5-7 million tons. The volumes decreased to 3,016 and 1,458 thousands when the fees increased to 6.9 and 7.5 USD/ton in 1993 and 1998. In 2003 the Ministry of Economic Development and Trade issued a decree called 'About Changing Rates for Ice-breaking Fleet Services on the NSR', which led to a substantial increase in the icebreaker fee to an average of 23USD per ton. The fee soared to 40.2 USD/ton in 2008 which seems unrealistically high. Is there a certain relationship between them? We used two rows of data in the Fig 3which will tell us pictorially.

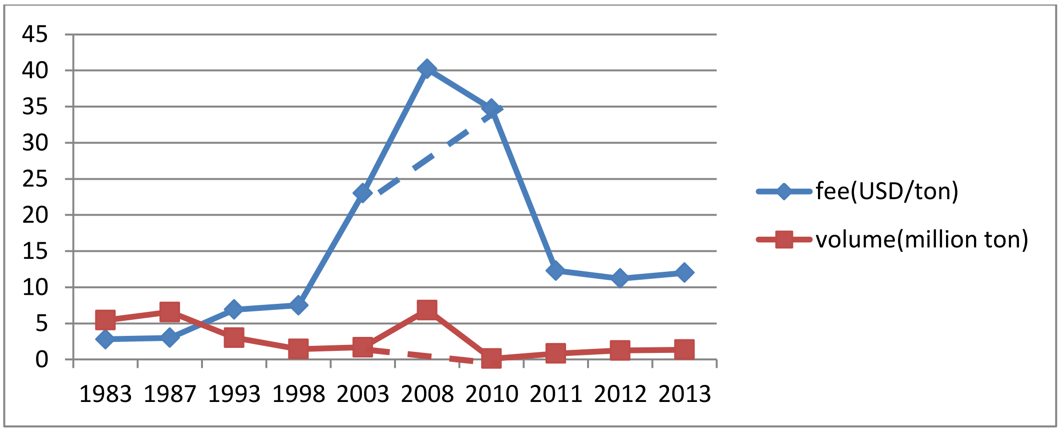


Figure 3.The Relationship between the Ice-break Fee and the Transport Volume

We can conclude from the figure that the ice-break fee has a negative effect on the transport volume in 1980s and 1990s. It is abnormal that the fee has a positive effect on the volume on the first 10 years of 21 century. But if we neglect the data in 2008 the ice-break fee, the figure looks much better, two kinds of data change in the opposite trend. Ice-breaking is the main problem and the only problem that can be solved recently. A reasonable ice-breaking rate with high level of ice-breaking service can make this route more attractive, however, the fact is NSR Administration can only offer low level ice-breaking service with relatively high price when compared with the Suez Canal fee. By decreasing the service level to cut down the ice-breaking fee is an unwise choice because it will result in the 'price-service paradox' [11]. From the aspect of the user of the Northern Sea Route, both the price and the service level are important.

2.3 The Main users of the Icebreaker Assistance Service

There are three main frequent users of the ice-breakers: the cargo ships for Russia's domestic transportation, the tankers which transport the natural resource out and the ships for international transportation. The cargo ships for Russia's domestic transportation are the oldest user of the ice-breakers. Even though the need for the domestic transportation decreased these years, it still plays an essential role in the market of icebreaker assistance service. The Arctic area is full of natural resource, especially some undiscovered oil and natural gas resources. There have account for approximately 240 billion barrels of oil and natural gas, which is almost 10 percent of the world's known conventional petroleum resources. LNG carriers and tankers go through the NSR to transport the liquefied nature gas and crude oil to the countries which have high demand for them. Since the increase of the volume of natural resource exported, more frequent and higher level icebreaker assistance service is needed these years. Ships for international transportation are the potential users of the service and will be the main users when the NSR become prosperous in the future.

3. Scheduling Model of the Icebreaker Assistance Service

Some notion should be identified before modeling. The request time mentioned refers to the expectation service time of the ship-owner.

To ensure the service quality, we assume that until finish the ongoing service task, the icebreakers are not allowed to serve other vessels. So inserting vessels into a fleet leaded by the icebreaker is not permitted.

The service principle used in our model is the First Come First Serve (FCFS) principle under which the requests from the ship-owner raised first will be processed first, is the most common algorithm for this problem [12]. But the 'processed first' is not necessary to be serviced first due to the distribution of the icebreakers, it only means the icebreaker which can navigate to its origin node will be allocated to serve the request first.

3.1 The model of the static ice breaker assistance service

Parameters:

k : The icebreakers in the service system, $k \in K$

i : The icebreaker assistance service request raised by the ship-owner, $i \in (1,2,...,n)$

i_+ : The origin node of the request i

i_- : The destination node of request i

d_{ij} : The voyage duration between node i and j

pr: The preparing time of the icebreaker before the next sailing (including ship maintaining, the supply of bunker and so on)

t_i : The expectation service of the request i

r_i^k : The return time of icebreaker k to the origin node of request i

r_i : The shortest return time of all the icebreakers

s_i^k : The service sequence of icebreaker k

$$\lambda_i^k = \begin{cases} 1 & \text{if request } i \text{ is servedby icebrekaer} k \\ 0 & \text{otherwise} \end{cases}$$

The ports along the NSR, icebreakers and merchant ships that want to go through the route constitute the ice-breaking service system (see Fig 4). The ice-breaker fleet is donated by k . When the service request i sent to the NSRA, the location of the users and the ice-breaker fleets will be taken into consideration. By weighing the service level and cost, only one icebreaker $k \in K$ will be sent to the origin node where i_+ the user stays in and escort the vessel to its destination node i_- .

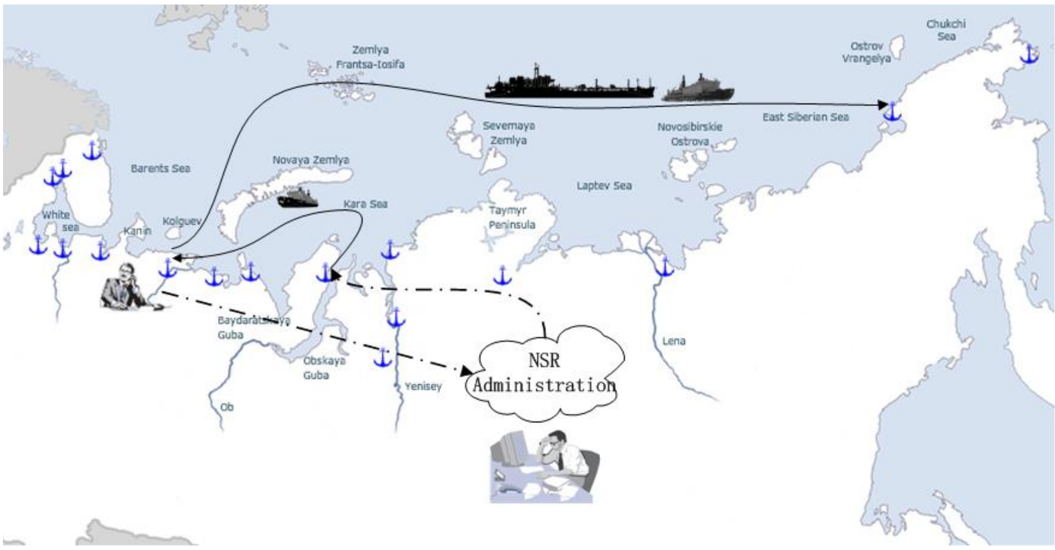


Figure 4.The Procedure of Ice-breaking Service

After the request has been sent, the owner of the merchant ship have to wait before the NSRA arrange an icebreaker for this request. Define w_i as the wait time of the request i. When the icebreakers arrive at the node i_+, they need time donated by pr to prepare for the next sailing. We define $f(s_i^k)$ be the mapping from s_i^k to node i, which is easy to operate in computer programming, but not easy in mathematic expression. So the mathematic formulation can be represented as follows:

$$W = \sum_{i=1}^{n} (r_i - t_i + pr)/n \tag{1}$$

$$G = g \sum_{k \in K} \left(\sum_{i=1}^{n} \lambda_i^k d_{i_+ i_-} + \sum_{1}^{S^k - 1} d_{f(s_i^k)_- f(s_i^k + 1)_+} \right)/n \tag{2}$$

$$h_i^k = \max\{s_j^k\} \quad j \in (1,2,3,..,i-1) \tag{3}$$

$$s_i^k = \lambda_i^k (h_i^k + 1) \tag{4}$$

$$s_0^k = 0 \tag{5}$$

$$r_i^k = \max\{t_i, t_{f(h_i^k)} + d_{f(h_i^k)_+ g(h_i^k)_-}\} + d_{f(h_i^k)_- i_+} \tag{6}$$

$$r_i = \max\{r_i^k\} \tag{7}$$

$$\lambda_i^k = \begin{cases} 1 & \text{if } r_i^k \le r_i^p \quad p \in K, p \ne k \\ 0 & \text{otherwise} \end{cases} \tag{8}$$

Function (1) represent the average waiting time of all the ship-owners. Empirical data are used to calculate the average fuel consumption of the ice-breaker per day, donated by g. The average fuel cost of all the request is illustrated by function (2). Function (3), (4) and function (5) set the service sequence of each icebreakers. Function (6) calculates the return time of each icebreaker. Function (7) and function (8) choose the best icebreaker for the request i.

In this model, we proposed an icebreaker assistance model under which the request raised first will be served first. Unlike other routing which build the models based on the theory of graph and minimize the total fuel cost or shorten the average waiting time. We construct our model based on the FCFS service which is popular in elevator service programming. The advantage of this model is that it respect the first raised request than the latter ones and easy to operate.

3.2 The FCFS Algorithm of the Dynamic Icebreaker Assistance Service

Unlike the static model, dynamic model is a more practical vision in which request will be generated randomly and will be inserted to the service system immediately. The insertion of the new request will influence the whole service arrangement before. Process the whole service procedure at one time is unable to realize, the system will only process the raised request. The procedure can is showed in Fig 5. At any time point, the scheduling of the icebreakers will be influenced by the service request (including the origin node, destination node and service time of the request) and the return time of all the icebreakers. The result of this decision-making will influence the return time of all the vessels when another request raises some time later.

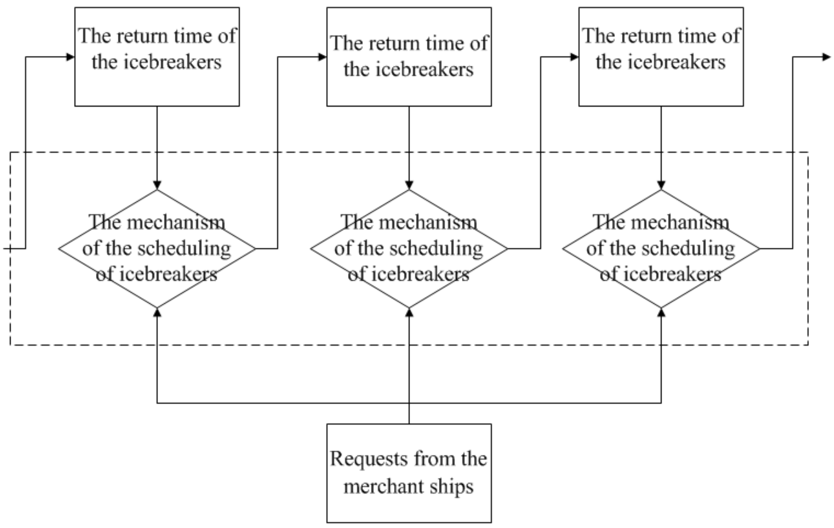


Figure 5.The Procedure of the Dynamic Icebreaker Assistance Service

In the dynamic service system, a clock $TIME$ for tracking the time is set in the model. At the beginning, $TIME$equals to 0, when the time equals to T, that means the end of the service. The request from the owner of merchant ship will be emerge at a random time, b_i is the interval between the request from merchant ship i and $i-1$. All the icebreakers have their return time donated by r_k. h_k is used to donate the location of the ice-breaker k. If the icebreaker k is stop at the port j, define $r_k = TIME$; if not, the return time equals to the time when the icebreaker comes to the port. To address this issue, we formulate d_{ij} to represent the destination port of vessel i. The navigating period between ports determine on the navigable condition, to simplify the research, we assume that the navigating periods between two ports are constants, donated by l_{mn}.The procedure of the dynamic algorithm is defined as follows:

1st step: Seta clock $TIME$. Let $TIME = 0$ at beginning; define T the end of the service.

2nd step: Generate the request time of the first user, the interval, and the location of the ice-breakers:

$$i = 1 \tag{9}$$

Generate port j where the vessel stays, the return time r_i^k, b_i and d_{ij} randomly. All the ice-breakers are defined to stay at port 1 ($j = 1$) at the beginning.

$$h_k = 1 \tag{10}$$

The values of the parameters above are used to initialize the clock which is donated by $TIME$, the return time of the icebreakers and the wait time of the users:

$$TIME = TIME + b_i \tag{11}$$

$$m = j, n = d_{ij} \tag{12}$$

$$r_k = \begin{cases} TIME & j = 1 \\ TIME + l_{mn} & j \neq 1 \end{cases} \tag{13}$$

If there's more than one icebreaker match the request, pick icebreaker k_i randomly.

$$w_i = Min l_{mn} \tag{14}$$

$$TIME_{k_i} = r_{k_i} + l_{mn} \tag{15}$$

$TIME_{k_i}$ is used to express the expected complete time of the service.

3rd step: If $TIME \leq T$, continue to 4th step; if not, end the procedure.

4th step: Generate the next user:

$$q_i = i, r_i = j \tag{16}$$

$$h_{k_i} = \begin{cases} d_{qr}, TIME > TIME_{K_I} \\ 0, \quad Otherwise \end{cases} \tag{17}$$

$$i = i + 1 \tag{18}$$

Generate j, b_i and d_{ij} randomly, then arrange the next icebreaker assistance service.

$$TIME = TIME + b_i \tag{19}$$

$$h_{k_i} = \begin{cases} d_{qr}, TIME > TIME_{K_I} \\ 0, \quad Otherwise \end{cases} \tag{20}$$

$$m = j, n = d_{ij} \tag{21}$$

$$w_i(k) = Min\{r_k - TIME\} \tag{22}$$

$$k_i = k \tag{23}$$

Back to 3rd step.

The total fuel consumption will be calculated after the total sailing period of the icebreakers is gained from the simulation.

4. Experiment

The icebreaker assistance service covers the most ports along the NSR, some ports are chosen for a simple simulation: Murmansk, Varandey, Dikson, Tiksi, Pevek and Provideniya. By analyzing the official data of the Northern Sea Route Information Office, the period during which merchant ships transit the NSR begins from the middle of June to the end of November. We set the service period equals to 182 days. The number of the ice-breakers equals to 18, which is the number of the ice-breakers Russia owns. Table 1 is the sailing time during any two ports among all the ports. Based on the data given, we do the simulation for 15 times with dynamic model, the results are shown in theTable 2 andFigure6.

Table 1. The Sailing Time during Any Two Ports among the Ports

	Murmansk	Varandey	Dikson	Tiksi	Pevek	Provideniya
Murmansk	0	4	7	14	20	23
Varandey	4	0	3	10	16	19
Dikson	7	3	0	7	13	16
Tiksi	14	10	7	0	6	9
Pevek	20	16	13	6	0	3
Provideniya	23	19	16	9	3	0

Table 2. Simulation Results (the number of Available Icebreakers Equals to 17)

Serial	Number of requests	Average waiting time (days)	Maximum waiting time (days)	Gap between average&maximum waiting time	fuel consumption/request number (thousand tons)
1	20	1.58	32	30.42	0.925
2	30	1.68	24	22.32	0.887
3	40	1.43	22	20.57	0.908
4	50	2.27	27	24.73	0.91
5	60	3.21	33	29.79	0.82
6	70	3.47	31	27.53	0.89
7	80	3.71	41	37.27	0.90
8	90	5.27	40	34.73	0.90
9	120	11.22	76	64.78	0.86

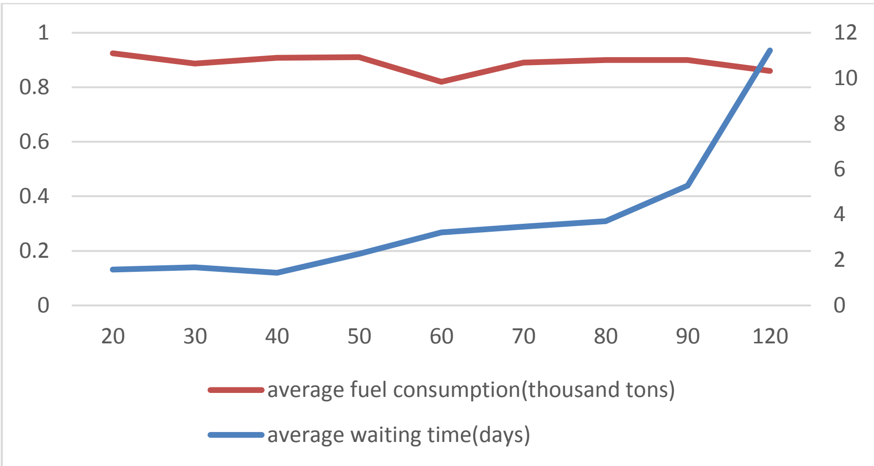


Figure 6.**The trend of the average waiting time and the average fuel consumption**

As we can see from Table 4, the dynamic model performances well in controlling the average waiting time small. The smallest waiting time is 1.43 days and the longest average waiting time is 11.22.But the gap between the average waiting time and the maximum waiting time looks huge under the FCFS principle. The minimum gap equals to 20.57 days when the requests is 40, but it's still too huge because the average waiting time is 2.27 days. This phenomenon can reflect the disadvantage of the FCFS principle: even though under this principle the average waiting time is controlled at a relative small scale, but it can't ensure that all the vessels can be serviced immediately, some vessels have to wait more than 20 days until the icebreaker come. We think these ship-owner won't wait such a long time in the modern world. When the number of merchant ships fluctuate fewer than80, the average waiting time and the average fuel consumption increase slowly. The average waiting time and total fuel consumption increase at big range since the number of users becomes bigger than 90. The maximum waiting time soar to 76 days when there are 120 users need the service. Such huge waiting time is totally unacceptable not only for the vessels, but also for the NSR because such a long waiting time may make the service time exceed the navigable time of NSR.

The average waiting time of vessel increases with the increase of the requests whereas the fluctuation of average fuel consumption (dividing the total fuel consumption of the number of the requests) is relative small, the average fuel consumption just fluctuates around 0.9 thousand tons per trip (Fig.6). It can be explained that when more vessels navigate through the NSR, the service cost changes little when the service quality decreases a lot.

5. Conclusion

The icebreaker assistance service is necessary for the navigating in the Arctic area due to the sea ice. Northern Sea Route is a potential route for commercial use. NSRA has to improve the competitive of this route by optimizing the icebreaker assistance service. We proposed both static and dynamic icebreaker assistance model in this paper. FCFS principle is utilized in our model. The experiment shows us that both the advantage and disadvantage of the dynamic model under FCFS: the advantage is that the average waiting time is controlled at a relative small scale; the disadvantage is that the gap between the average waiting time and maximum waiting time is too huge, some vessels have to wait long time before being served. Even though this model is not good enough, we think it can be used in real world operation after being improved. Another result of the experiment is that the average fuel consumption is stable with the increase of the number of request, but the service quality (waiting time) decrease. It gives NSRA a signal add more icebreakers into to service system will increase the service quality, but the cost will rise. What's more, the decrease of the sea ice in the Arctic area is a great obstacle to the investment of the icebreaker, especially when we consider the high capital cost of ice-breakers.

This research is an attempt, some factors are simplified (e.g., the different operation of the icebreakers, the capital cost, the uncertainty during navigating). When taking more factors into consideration, the ice-breaking service simulation system will be complex. The random arrival time of merchant ships plays an important role in the scheduling of the ice-breaking service, which will result in huge maximum waiting time. The study in the future can put more focus on this field.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

Acknowledgements

The research is supported by National Science Foundation (G71301101).And the valuable comments of external anonymous reviewers are also gratefully acknowledged.

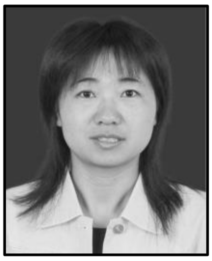
References

[1] M. Stopford, “Maritime Economics (3rd edition)”, Routledge, New York, (**2009**).
[2] J. Rodrigues,“The rapid decline of the sea ice in the Russian Arctic”, Cold Regions Science and Technology, vol. 54, **(2008)**, pp. 124-142.
[3] A. G. Granberg, “The northern sea route: trends and prospects of commercial use”, Ocean & Coastal Management, vol.41, (**1998**), pp.175-207.
[4] T.S. Jørgensen, “Synoptic ice characteristic of the northern sea route”, International Challenges, vol.12, no.1, (**1992**), pp.68–74.
[5] R. Laulajainen,“The Arctic Sea Route”, International Journal of Shipping and Transport Logistics, vol.1, no.1, (**2009**), pp.55–73.
[6] T. Valsson, G. F. Ulfarsson, “Future changes in activity structures of the globe under a receding Arctic ice scenario”, Futures, vol.43, (**2011**), pp.450-459.
[7] A. G. Granberg. “The northern sea route: trends and prospects of commercial use”, Ocean & Coastal Management, vol.41, (**1998**), pp.175-207.
[8] M. Liu, J. Kronbak,“The potential economic viability of using the Northern Sea Route (NSR) as an alternative route between Asia and Europe”, Journal of Transport Geography, vol.18, (**2010**), pp.434-444.
[9] N. Hong, “The melting Arctic and its impact on China’s maritime transport”, Research in Transportation Economics, vol. 35, (**2012**), pp. 50-57.
[10] A.G. Gorshkovsky,“Rules to be Followed on the Northern Sea Route”, Arctic Operational Platform (ARCOP) Workshop 1–9 Participant Statistics, Helsinki (**2003**).
[11] E.J. Wilson,“The Relative Importance of Supplier Selection Criteria: A Review and Update”, International Journal of Purchasing and Materials Management, vol.30, no.2, (**1994**), pp.34-41.
[12] X. Fan, M. Jonsson, J. Jonsson, “Guaranteed real-time communication in packet-switched networks with FCFS queuing”, Computer Networks, vol. 53, no. 3, (**2009**), pp. 400-417.

Authors

Yi Ding. He is currently a Lecture of Logistics Research Center at Shanghai Maritime University in China. He received the Master degree of Software Engineering from East China Normal University. Ding’s current research interests include port management and intelligent algorithm.

Weiwen Zhou. He was born in 1989.6,he incepted his master degree in Shanghai Maritime University in 2014 and his major is Management Science& Technology. His current research interests include bulk cargo transportation, schedule of shipping line, supply chain management algorithm.



DongmingXu. Her Current position: Ph.D student, logistics researcher center, Shanghai Maritime University in China.

Scientific interest: logistics network design and optimization; green supply chain management.

Experience: Participate in five planning for enterprise, three municipal projects, and one National Natural Science project.

