The Scheduling of Icebreaker Assistance Service Along Northern Sea Route on VRPPD Model

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***Abstract* — The melting of the sea ice in the Arctic area increases the possibility of exploiting the Northern Sea Route (NSR) for economic reasons. Icebreaker assistance service is necessary for the users of NSR. This paper proposes the icebreaker assistance service scheduling problem in the NSR to focus on the arrangement of the service schedule. An icebreaker assistance service model is constructed based on the Vehicle Routing Problem with Pickup and Delivery (VRPPD) model but, differently, our model considers both the total voyage distance of all the icebreakers and vessel's extra navigating distance ratio (ENDR). To solve problem of such complexity, elitist non-dominated sorting genetic algorithm (NSGA-II) is used to find non-dominated solutions. We conduct experiments on various scenarios to test the influence of the quantity of icebreakers. The experiment results show valuable insights into the operation of the icebreaker assistance service along NSR.**

Keywords - Northern Sea Route; icebreaker assistance service; VRPPD; NSGA-II

I. INTRODUCTION

The melting of sea ice in the Arctic Ocean caused by the globing warming roused the interest of exploiting NSR for commercial use. Except for the Russia's domestic transportation cargo ships, the tankers which transport the natural resource out, some ship companies also made their test navigation through the NSR these years. China's Maritime Silk Road strategy emphasize the using of sea routes for cargo transportation between Far East and Europe. Navigating through the NSR will save a lot of shipping distance, hence rouses great interests in the shipping industry. Building a new shipping network including NSR will not only attribute the shipping industry, but will also attribute the economic cooperation between east and west. However, the climatic conditions making navigating through the NSR more difficult than navigating through some traditional routes. Despite the fact that sea ice melting rate within Arctic area is faster than previous (Joshua Ho, 2010), ice condition is still an obstacle to navigation [1]. As a consequence, icebreaker assistance for convoy is necessary for the vessels entering the NSR. So, an efficient scheduling of icebreaker assistance service is needed.

The focus of the present paper is on the scheduling of the icebreaker assistance service which has not yet attract adequate research interest. This paper proposed a scheduling model to design optimal routes for icebreakers. The icebreakers have to navigate through seaway network to fulfill the icebreaker escort requests: escorting the merchant ships from their origin ports to destination ports under time constraints. Each icebreaker is assigned with a given service capability: the maximum number of ship the icebreaker is capable to escort at any given time period. During the navigation leaded by the icebreakers, the vessel may navigate beyond the direct navigation distance which we referred as extra navigation distance. From the interests of the ship-owners, the extra navigating distance will cost extra fuel cost. The objectives of the model are to minimize the total voyage distance of all the icebreakers and minimize the extra navigation distance of vessels under a set of constraints. From the methodological perspective, our model is constructed based on the Vehicle Routing Problem with Pickup and Delivery (VRPPD) model with the characteristics of icebreaker assistance problem. Considering the complexity of such problem, we use elitist non-dominated sorting genetic algorithm (NSGA-II) to find non-dominated solutions. The key contribution of this paper is its attempt to scheduling the icebreaker assistance service along NSR by using the knowledge in VRP.

II. LITERATURE REVIEW

According to Arctic Council's definition, Northern Sea Route is the sets of Arctic marine routes between Kara Gate in the west and Bering Strait. These routes run through 5 sea areas, including Barents Sea, Kara Sea, Laptev Sea, East Siberian Sea and Chukchi Sea (Ivanov and Ushakov, 1992) [2]. Unlike other shipping lanes, NSR is not a constant shipping lane, it varies distinctly at different navigating periods (Kolodkin and Volosov, 1990) [3]. The average length of these routes is approximately 3000 nautical miles, the actual distance is influenced by the sea track selected. The sea ice plays an important role in NSR navigation, it not only determine the practical shipping route, but also endanger the safety of the ships and the crew. In navigable seasons (approximately from June to November), high concentrated ice (ice massifs) is a main obstacle to NSR navigation. Despite the tough shipping environment, NSR attract people for the sake of its short distance. The navigation distance via the NSR from Northwest-Europe to Far East is approximately 40% shorter than navigating through the Suez Canal (Halvor Schøyen and Svein Bråthen, 2011) [4].

Nowadays, the exploiting of the nature resource and the voice clamoring for using the NSR as an alternative route to the dominating routes in the world maritime network by dint of its shorter sailing distance than classical routes (the Panama route and the Suez route) rouse the attention to icebreaking service. Miaojia Liu and Jacob Kronbak (2010) suggest that it is important to pay particular attention to the icebreaker assistance service [5]. They compare the annual profits generated by the routine service via the Suez Canal and the NSR service under different scenarios, point out that lower the ice-breaking fee, higher the competitiveness of the route. The icebreaker fee is determined by the capacity of the ships, ship's ice-class, distance of the icebreaker support and the navigation period. The aim of the icebreaker fee is to cover the capital and maintenance cost of the icebreakers, then make the service profitable. Khvochtchinski and Batskikh (1998) point out that it is necessary to increase the volume of transit cargo per icebreaker for the purpose of making the service more profitable and decrease the icebreaker fee [6]. Except the service fee, the service quality also influences the competitive of the NSR. We hold the view that the service quality can be improved through an effective scheduling of the icebreaker service.

Due to the lack of such study, there are almost no prior papers about the scheduling of the icebreaker service. However, from the viewpoint of the model feature, our problem is similar to the Vehicle Routing Problem with Pickup and Delivery (VRPPD), more precisely, the dial-a-ride problem (DARP, VRPPD under dial-a-ride scenarios). In the VRPPD, a heterogeneous vehicle fleet based at multiple terminals must satisfy a set of transportation requests. Each request (could involve goods or persons) is defined by a pick point and a corresponding delivery point and a demand to be transported between these locations (Toth & Vigo, 2001) [7]. The principle objective of the problem is to decrease the cost of the system and minimize the size of the fleet, see Shoshana Anily (1994), M. Desrochers et al. (1990) and Dumas et al. (1990) [8][9][10]. Time window is always referred to when considering the service quality especially in the DARP. Vehicle routing problem with time windows can be bifurcated into two branched according to the characteristics: the vehicle routing problem with hard time windows (VRPHTW) and vehicle routing problem with soft time windows (VRPSTW). Homberger and Gehring (2004) considering the time window while propose a two-phase hybrid metaheuristic for the vehicle routing problem [11]. Mester and Bräysy (2005) designed least cost routes for a fleet of identical capacitated vehicles to serve the customers within pre-specified time windows [12]. To adapt the research to practical operation in real world, several researches propose the scheduling problem with soft time window by accounting the late arrive time penalties. Qureshi et al. (2009) presents an exact approach for the vehicle routing problem with semi soft time window (VRPSSTW) [13]. Despite the waiting time, another factor also impacts the service quality: the extra travel distance and time. It is typically obvious in DARP allow ride-sharing, when passengers share the same vehicle, some of the passengers in the vehicle will undergo extra travel distance and time as a result of the drivers' action of picking up or sending other riders. Baoxiang et al. (2014) give a discount to the passenger when the extra travel distance is caused in their mathematical model in which the people and parcels are allowed to be allocated in the same taxi [14]. Our problem is similar to such problem in this aspect due to an icebreaker is always scheduled to serve more than one vessel, each has its pre-specified pick up node and destination node. Notwithstanding, there's a huge difference between our problem and the DARP allow ride-sharing: extra fuel cost. Extra navigating distance will cause extra fuel cost, which will damage the interests of the ship-owners. To balance the interests of both sides, we developed a bi-objective icebreaker assistance model.

III. THE SCHEDULING MODEL OF THE ICEBREAKER ASSISTANCE SERVICE

A. The Icebreaker Assistance Service Problem

The icebreaker assistance service system is composed by the vessels, the provider of icebreaker assistance service and icebreakers (under the state flag of Russian Federation) authorized to offer the service. The NSRA provides the information about the necessity to use icebreaker assistance under heavy, medium and light ice conditions while sailing in the water area of the NSR. If the ship meets the icebreaker assistance necessity, the ship-owner will call the organizations that render such service. In our model, we set a center unit in the system. Once the ship-owners send the icebreaker assistance requests to the center unit, the center unit will analyze the details about the time of the beginning time of the service, the departure and the destination of the vessels first, then allocate the optimal icebreakers to escort the vessels.

B. The Scheduling Model of the Icebreaker Assistance

In the scheduling model, let $K = \{k \mid k = 1,2,...m\}$ donates the set of icebreakers and the number of icebreakers equals to m . The number of vessels which need service equals to n . An undirected graph $G = (V, A)$ is constructed where V donates the node set and A donates the arc set (the direct paths between two ports). A set of vessels scattered along the NSR require the icebreaker assistance, each vessel corresponds to two nodes: the origin node belongs to subset V_1 which represent both the vessels and the origin port, and the destination nodes belong to subset V_2 represent the destination port.

A clock ζ_i^k for tracking the time that icebreaker k arrives at port i is set in the model and ζ_i^k equals to zero at the beginning of the service. $t_{ij}(i, j \in V)$ donates direct travelling duration between stop i and stop j , which is a

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calculation of distance divided by speed. $e_i^o (i \in V_1)$ represents the earliest departure time. The icebreaker is allowed to arrive earlier than e_i^o, but have to wait for the departure time e_i^o. The icebreaker and the fleet it serves will leave the node at T_i^n. l_{i+n}^d is used to donate the latest arrival time of vessel $i \in V$. $S_j^k (j \in V)$ donates the port visiting sequence of icebreaker $k \in K$.

The service capability (maximum number of the vessels that an icebreaker can serve at the same time) is donated by U. We use u_i^k to represent the number of the vessels the icebreaker k serves after visiting the port $i \in V$, we have to make sure that u_i^k doesn't exceed U. The ship-owner will not be critical about the voyage period as long as they will be sent to the destination earlier than the latest arrive time l_{i+n}^d, but the voyage distance is the factor directly influences the fuel cost during the navigation, so a shorter navigation distance is more preferable for the ship-owners. We impose the index of extra navigation distance ratio (ENDR) to describe the navigation efficiency of each vessel. The ENDR Φ_i of vessel $i \in V_1$ can be defined as:

$$\Phi_i = 1 - d_{i,i+n} / D_i \tag{1}$$

$d_{i,i+n}$ is the direct voyage distance from the origin port to the destination port of vessel $i \in V_1$, whereas D_i is the actual voyage distance. For example, the direct voyage distance from port i to port $i+n$ equals to $d_{i,i+n}$, if there's no ports visiting between i and $i+n$, the actual voyage length equals to $d_{i,i+n}$. However, if in real practice service sequence is $(i, j, j+n, i+n)$ which means the fleet leaded by the icebreaker have to visit port j and $j+n$ first, the actual voyage length of vessel i is $d_{i,j} + d_{j,j+n} + d_{j+n,i+n}$.

The actual voyage length can be calculated as follow:

$$D_i = \sum_{\alpha = s_i^k}^{s_{i+n}^k} d_{g(\alpha), g(\alpha+1)} \qquad i \in V_1 \tag{2}$$

In function (2), $g(\alpha)$ is the mapping function from the service sequence s_i^k to the node α. The ENDR of the ship-owner of the vessel i is positively correlated to the actual voyage distance D_i, hence positively correlated to the number of ports visiting between origin port i and $i+n$ ($i \in V_1$). When there's no ports arranged to visit between the origin port and the destination port of the vessel i, the ENDR equals to 0. Otherwise, the ENDR will increase with the increase of the number of ports visited while picking up or delivering other vessels.

Then the scheduling of the icebreaker service become a bi-objective decision making problem.

$$\min f_1 = \sum_{i,j \in V} \sum_{k \in K} d_{ij} x_{ij}^k \tag{3}$$

$$\min f_2 = [\sum_{i=1}^{n} (1 - d_{i,i+n} / \sum_{\alpha = s_i^k}^{s_{i+n}^k} d_{g(\alpha), g(\alpha+1)})] / n \tag{4}$$

$$\sum_{i \in V_1 \cup V_2} x_{ij}^k - \sum_{i \in V_1 \cup V_2} x_{ji}^k = 0 \quad \forall k \in K, j \in V_1 \cup V_2 \tag{5}$$

$$\sum_{k \in K} \sum_{j \in V_1 \cup V_2} x_{ij}^k = 1 \quad \forall i \in V_1 \tag{6}$$

$$\sum_{j \in V_1 \cup V_2} x_{ij}^k - \sum_{j \in V_1 \cup V_2} x_{j,i+n}^k = 0 \quad \forall k \in K, i \in V_1 \tag{7}$$

$$\zeta_0^k = T_0^k = 0 \qquad \forall k \in K \tag{8}$$

$$T_i^k = \begin{cases} \zeta_i^k & \zeta_i^k \ge e_i^o \\ e_i^o & \zeta_i^k \le e_i^o \end{cases} \quad \forall k \in K, \forall i \in V_1 \tag{9}$$

$$T_i^k = \zeta_i^k \qquad \forall k \in K, \forall i \in V_2 \tag{10}$$

$$\zeta_j^k = (T_i^k + t_{ij}) x_{ij}^k \ \forall k \in K, \forall i \in V_1 \cup V_2, \forall j \in V_1 \cup V_2 \tag{11}$$

$$\zeta_i^k \le l_i^d \qquad \forall k \in \mathbf{K}, \forall i \in \mathbf{V_2} \tag{12}$$

$$s_0^k = 0 \qquad \forall k \in K \tag{13}$$

$$s_j^k = (s_i^k + 1) x_{ij}^k \qquad \forall i, j \in \mathbf{V} \tag{14}$$

$$u_0^k = 0 \qquad \forall k \in K \tag{15}$$

$$u_j^k = x_{ij}^k (u_i^k + 1) \ \ \forall i \in V_1 \cup V_2, \forall j \in V_1, \forall k \in K \tag{16}$$

$$u_j^k = x_{ij}^k (u_i^k - 1) \ \ \forall i \in V_1 \cup V_2, \forall j \in V_2, \forall k \in K \tag{17}$$

$$0 \le u_i^k \le U \qquad \forall i \in V, \forall k \in K \tag{18}$$

The goal of the center unit is to decrease the total voyage distance of all icebreakers (which will decrease total fuel cost of the icebreakers), but the each vessel's extra voyage distance should also be decreased to decrease the ENDR. The objective function (3) minimizes the total voyage distance of the icebreakers and the objective function (4) minimize the average ENDR of the vessels.

Constraint (5) characterizes the flow structure. Constraint (6) ensures that one request will be served by one icebreaker at most once. Constraint (7) ensures that if the icebreaker is sent to serve the vessel, it must escort the vessel to its destination. Constraint (8) ensures that the arrival time and the departure time equal to zero at the beginning. Constraints (9), (10) and (11) illustrate the relationship between the arrival time and the departure time at each node. Constraints (12) ensure that all the icebreakers have to arrive the ports before the last arrival time of each request. The service sequence of each icebreaker is counted by constraints (13) and (14). Constraints (15), (16) and (17) count the number of vessels served by each icebreaker after visiting the nodes.

Constraint (18) limits the number of vessels in the fleet escorted by the icebreaker.

IV. NSGA-II FOR SOLVING ICEBREAKER ASSISTANCE PROBLEM

The problem raised in our paper belongs to the class of NP-hard problem with bi-objectives. Elitist non-dominated sorting genetic algorithm (NSGA-II) is widely used to solve such problem due to its advantage of having a better spread of optimal solution and less computational complexity. NSGA-II is based on genetic algorithm (GA) and use non-domination sorting procedure to create Pareto fronts. To avoid NSGA's disadvantage (high computational complexity of non-dominated sorting, lack of elitism and need for specifying the sharing parameter), Deb et al. (2002) proposed NSGA-II with the properties of a fast non-dominated sorting procedure, an enlist strategy and a parameter less approach [15]. The main procedure of using NSGA-II to solve our problem is showed as follows:

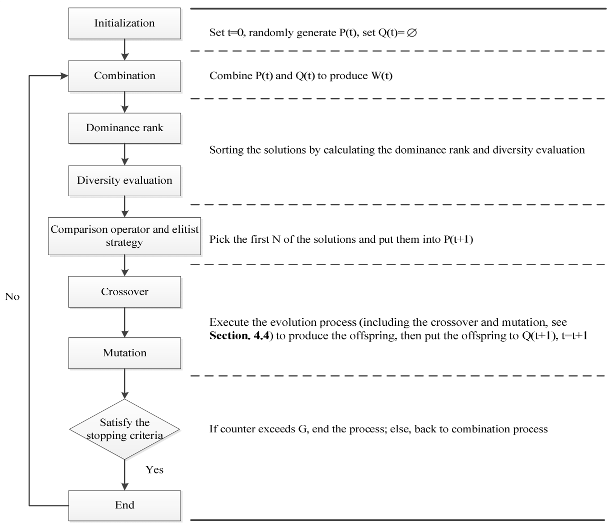

Figure 1. The process of the NSGA-II.

A. *Chromosome Coding and initialization*

At the first step, we use the integral number coding of all the nodes in the graph to represent solutions. For example, if there are 4 service requests served by 3 icebreakers, we use natural number 1-8 to represent the departure and destination nodes to be visited. Each request's departure node and its corresponding destination node should be in the same route and the departure node should occur before the destination node in a given route sequence. To make sure the quality of the initial solutions, we imposed the concept of minimal requests (Chevrier et al, 2012): the minimal requests are the requests which have to be picked up first, rank the departure nodes of these requests after other routes in any routes will cause these requests can't be served [16]. The initial solutions are generated in the following procedure:

Step 1: find the minimal requests set V_{min}

Step 2: randomly assign the minimal requests to $|\mathbf{V}_{\min}|$ routes.

Step 3: for the rest of the requests, randomly add them to the existing routes. If there is no possible to adding them to the existing routes, create a new route then add them to the new route.

B. *Dominance rank and density of the solutions*

In NSGA-II, each solution $r \in W(t)$ will be compared with other solutions to check whether it is dominated. Fitness function is utilized to evaluate the individuals of each function. The evaluation function is shown in Eqs. (19).

$$\text{Fitness function vector} = \begin{cases} f_1 + M_1 \\ f_2 + M_2 \end{cases} \quad (19)$$

Where f_1 and f_2 are the objective functions, M_1 and M_2 are penalty indexes to sort solutions dissatisfy all the constraints at low dominance rank. We calculate four entities:

n_r : number of solutions which dominate solution r

S_r : set of solutions which are dominated by solution r

Z_i : set of ith non-domination rank

r_{rank} : non-domination rank of solution r

After we calculate the non-domination rank, we evaluate the solution spread to make sure the quality of solutions. Then we use crowding distance to describe the spread of solution, define the crowding distance of the boundary solutions equals to infinity. For the other solutions, crowding distance can be calculated in two steps. In the first step, we rank all the solutions according to the values of f_1, then the solutions will be ranked as $\{r_i \mid i = 1, \ldots 2N\}$ in ascending order. In the second step, the crowding distance can be calculate as follows:

$$d_{r_i} = (f_2^{r_{i+1}} - f_2^{r_{i-1}}) / (f_2^{\max} - f_2^{\min}) \quad (20)$$

C. *Comparison Operator and elitist strategy*

The comparison procedure can be express as follows: compare the value of r_{rank} of two solutions, the smaller one is the better solution; if r_{rank} of these two solution are assigned with the same value, compare the crowding distance, solution with larger crowding distance is better. The elitist strategy will use the results of the comparison procedure.

NSGA-II use elitist strategy to prevent the loss of good solutions by mix the parent and offspring. At first, we mix the parent $P(t)$ and its offspring $Q(t)$ of a certain generation t to construct $W(t)$. The population of $W(t)$ is $2N$. Use comparison operator to generate parent $P(t+1)$, consists of first N good solutions from $W(t)$. Then we produce offspring $Q(t+1)$ by using genetic operators.

D. *Genetic operators*

Because the solutions in this article consists several vectors which represent the routes, traditional crossover techniques can't be used in our research. Chevrier et al. (2012) proposed a special crossover operator for dial-a-ride problem, it can be applied to solve our problem [16]. Let p_1 and q_1 the solution selected from the population of parent, they produce the offspring solution q_2 through following way:

Step 1: Randomly choose p_1 and q_1 .

Step 2: Randomly choose λth vector from p_1 , remove the requests that matching those in λth vector from q_1

Step 3: assign it to λth vector in q_1 randomly. If the λth vector of q_1 is a null vector, the origin node and the end node of the icebreakers should be allocated to the beginning and end of the vector first.

Correspondingly, q_1 will be created in the same way. These process doesn't neglect the unfeasible solution because those solutions will be valued in the dominance ranking process.

The mutation operator can be express as follows: firstly, choose one vector in an offspring solution and choose one request (two corresponding points) from this vector; secondly, randomly inserting them into another vector.

V. EXPERIMENTS AND ANALYSIS

A. *Experiment design*

The experiment proposes a service network cover principal ports in NSR area, the port-to-port matrix of the navigating distance and was built based on a navigation information software Netpas Distance, a corresponding port-to-port matrix of the navigating duration is also constructed in the premise that the average speed equals to 8.8 knots (the average speed of 2013).

We set the service period within the historical transit data. We generate our requests located randomly in the service network with corresponding destination node of the service (note: the origin node and destination node of the icebreaker service only reflect the navigation flow in icebreaker assistance network). The time windows are produced in the following way: earliest departure time e_i^o is produced randomly within the service period. The latest arrival time of the vessel is set to $e_i^o + \gamma t_{i,i+n}$ which means the ship-owners only can bear at most γ times of the normal navigating duration. γ is assigned with the value of 3 in the first part of the experiment.

B. *Results Analysis*

Fig. 2 shows the results of the first part of our experiment where when we allocate 25 icebreakers to serve 50 requests. The shape of non-dominated solutions is convex, total voyage distance of all icebreakers and average extra voyage ratio are negative correlated which means it is impossible for ship-owners and icebreaker assistance providers to achieve a win-win results. From the interest of the service provider, reducing the operation and voyage cost of the icebreakers is more important, so they prefer the solutions with less total voyage distance of all icebreakers. Solution A (8953.82, 0.8362) is the best solution for service provider. However, from the aspect of vessels, less extra voyage distance ratio means less waste of cost, so they prefer the solutions with less extra voyage distance ratio and solution B(11035.76, 0.2092). But considering the future development of NSR, the icebreaker assistance should be competitive enough to attract more vessels to navigate through, the icebreaker assistance service provider will sacrifice more total voyage distance of the icebreakers to decrease the average extra navigating distance ratio.

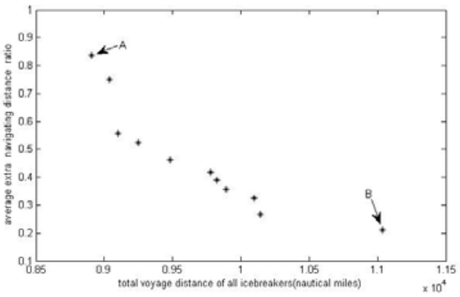

Figure 2. Non-dominated solutions.

Fig. 3 illustrates how the quantity of icebreakers influence the results. We do other 3 experiments by setting the number of icebreakers 23, 27 and 29. We observed that with the increase of the number of icebreakers, the dispersion of non-dominated solution shifted. With a fixed total voyage distance of all icebreakers, the average extra navigating distance ratio decreases along with the increase of the quantity of icebreakers. If the average extra navigating distance ratio is fixed, the total voyage distance of all icebreakers decreases along with the increase of the quantity of icebreakers. This means the provider of icebreaker assistance service can save a lot of voyage cost (especially the fuel cost). However, the capital cost of the icebreakers which influence the investment of more icebreakers is not considered in this article. We suggest that the providers of the service should balance the capital cost, voyage cost and the service quality before arranging the proper quantity of icebreakers.

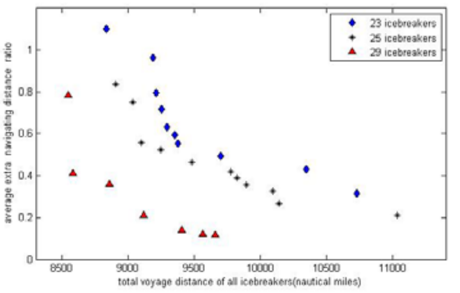

Figure 3. The influence of the number of icebreakers

VI. CONCLUSION

In this paper, we research the icebreakers assistance service along the NSR, and then raise a scheduling problem of this kind of service. We find this model is similar to VRPPD problem in some respect. But we can't neglect the obvious difference: the icebreakers pick up vessels, not cargos. The vessels follow the icebreakers not placed in the icebreakers, but followed the icebreakers. As a result, we have to consider the extra navigating distance of the vessels. So we propose a multi-objective scheduling model of the icebreaker assistance service considering both the total distance of the icebreakers and the average extra navigating distance of the vessels.

The experiment results show us that the total voyage distance of all icebreakers in the service system and the average extra navigating distance are negative relative. Decreasing the total voyage distance of icebreakers blindly is not recommended from the perspective of the developing of NSR because that will increase the users' ENDR, then make the NSR less competitive than Suez Canal. Both the users of such service and the operator of such service can be benefited by increasing the quantity of icebreakers because sets of better non-dominated solutions will be produced through this way, but the investing more icebreakers depends on the future development of this sea route. China's 'Maritime Silk Road' strategy will push the development of NSR, as a result, more vessels will navigate through this sea route in the next decades. Taking this into account, investing more icebreakers could be favorable. Beside the icebreakers assistance, pilot ice assistance, navigational-hydrographic and hydrometeorologic support and the guidance of ships along the NSR should also be improved.

In this paper, we attempt to schedule the icebreaker assistance service from the aspect of academic. The problem we raised will be a branch of the VRPPD and is worth to be researched in the future. However, the calculation of the non-dominated solutions is not the end of this research. Due to lack of the real practical data, we can't find at which point of extra navigating distance ratio of each vessel will make the NSR less competitive that Suez Canal. In our future research, we will make a comparison between the voyage cost of navigating through the NSR and the Suez Canal from the interest of the ship-owners under different solutions from the non-dominated solutions. Adding NSR into the world existing world maritime network and analyze how NSR influence the world ocean transportation is also a potential research area.

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