An Research on the design and optimization of shipping routes in the Arctic

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Abstract. In the design and research of the Arctic route, the route design can be interfered by other factors. This paper studies the route design and optimization after considering the interference of external factors. According to the external environment factors to design the arctic route weather route, the first arctic route design model was established, using the method of dynamic programming. Therefore, it is necessary to continuously determine the shortest sailing time of the ship, namely the actual sailing speed of the ship. According to the sailing conditions of the ship in different environments, so that the highest degree of navigation safety can be achieved, and the route optimization problem is transformed into a multi-stage decision-making problem. The global optimal solution is obtained by looking for the local optimal solution of each stage. Combined with the original Arctic route model, the meteorological route is optimized. By separating the present period from the future period, the present and future benefits are considered together. By determining the stage index function and the optimal index function, the basic equation of dynamic programming is established. The Pareto front curve corresponding to the requirements of the shortest voyage time and the voyage safety is given, that is, the optimal solution function curve of the two objectives. The influence between the shortest voyage time and the voyage safety is weighed comprehensively, and the optimal solution is obtained by combining the actual situation of the ship during the voyage, that is, the route optimization is completed. Finally, the optimized Arctic route is simulated and evaluated in an electronic computer simulation system with similar environment.

1. Introduction

The Arctic route is a maritime route that crosses the Arctic Ocean and connects the Atlantic and Pacific oceans. The Arctic route includes the northeast route connecting Eurasia, the northwest route through Canadian Arctic Arch. and the Arctic route directly across the North Pole. The northeast route runs from western European and Nordic ports to the coast of Siberia, bypassing the Bering Strait and reaching ports in China or Japan. In August 2007, a NASA satellite image showed that for the first time, both the Northeast and Northwest shipping routes had been fully melted[1], and the Arctic Ocean was expected to be ice-free by 2040[2]. In the summer of 2009, two German cargo ships, Eamie and Vision, arrived in Rotterdam, the Netherlands, from South Korea via the North-East route, marking the start of the commercial operation of the Arctic route[3]. In 2012, the Chinese research ship Xue Long sailed its first voyage to the northeast. In 2017, China and Russia proposed to jointly build an "Ice Silk Road", including the Arctic route. On September 17, 2019, the "Tianxi" ship of COSCO Special Shipping Co., Ltd. shipped nearly 30,000 tons of paper pulp back from Helsinki, Finland, marking the successful completion of COSCO Special Shipping -- Shandong Port Group's first voyage to the Arctic in 2019. Therefore, Arctic shipping routes have become the focus of international attention because of their
economic benefits and strategic status. The great development prospects of the Arctic shipping routes are closely related to the following factors:

1. The decrease of sea ice has created better navigational conditions for future Arctic navigation;
2. The Arctic is rich in energy and mineral resources, and the transportation of such goods cannot be done without ships sailing in the Arctic;
3. Compared with ships passing through Suez, using the Arctic route can save a lot of time and cost;
4. The adoption of Arctic shipping routes is conducive to energy conservation and emission reduction of ships;
5. The rapid development of icebreaker technology has provided a strong guarantee for ships sailing in the Arctic.

In recent years, relevant research results have emerged continuously, and the study of Arctic shipping routes is becoming a constantly developing and evolving field of knowledge. Accurate understanding of the design and research of Arctic shipping routes is of great significance for subsequent research.

**Research status at home and abroad:**

Based on literatures related to Arctic shipping routes in CNKI database and Web of Science core collection database, the results show that:

1. The research on Arctic shipping routes at home and abroad started in 2007 and 1991 respectively, and became a research hotspot in 2014 and 2015. The annual distribution trend of domestic research literature is basically consistent with the latter two stages in the world.
2. Scholars in various fields actively participated in the research. The scholars who published the most papers at home and abroad were Li Zhenfu (Dalian Maritime University) and Ehlers S (Russian Academy of Sciences). The research was mainly conducted by individuals with little team cooperation.
3. The School of Transportation Management of Dalian Maritime University and the Russian ACAD SCI (Russian Academy of Sciences) are the core of the cooperation network of domestic and foreign research institutions respectively, and there is less cooperation among different research institutions, and less cross-regional and cross-sectoral cooperation;
4. Literature keywords are becoming more and more diversified, and research topics and methods are becoming more and more diversified; The research topics of Arctic shipping routes focus on the economic feasibility of Arctic shipping routes, the impact of Arctic shipping routes on economic trade and shipping network, the navigation environment and safety of Arctic shipping routes, and the policy and implementation of national Arctic shipping routes. Future research hotspots in the field of Arctic shipping routes may include the integration of Arctic shipping routes and the Ice Silk Road, the human environment of shipping routes, the safety of shipping routes, and joint research.

2. Problem description and modeling

2.1. Design of meteorological routes affected by the special Arctic Marine environment

Most of the Arctic shipping routes are located in the Arctic Circle, and the factors affecting the navigation environment of the Arctic shipping routes are complex and changeable. The factors affecting the navigation environment of the Arctic shipping routes can be classified into three categories: natural environment, navigational AIDS and human environment factors. On weather route of the ship design process, the arctic route navigation environment were the main influencing factors, sea ice is the main limiting factors, the key area of ice will directly influence the course of opening, influencing the airline navigation key areas of the east Siberian sea, Novosibirsk, islands, north to the islands, laptev sea and willy to sergei Kirov kits based channel islands; Affecting the southern route of the Northwest Passage, the key areas are Victoria Strait, Peel Strait and Barrow Strait; The key areas affecting the northern route of the Northwest Passage are McClure Sound and Viscount Melville Sound. As the global climate warms, the total amount of Arctic sea ice decreases and the mobility increases, and the distribution of sea ice varies during the navigation period each year, leading to the instability of navigation routes. Therefore, it is necessary to strengthen the ability of Arctic sea ice monitoring and forecasting, so as to provide guarantee for the utilization of Arctic shipping routes. The design of the
Arctic weather route is largely limited by the extreme adverse environment, and different weather routes can be designed in different periods. Navigable stage with melting sea ice in the arctic route changes, North-East average navigable stage is mid to late July to mid to late October, across the opening period mainly concentrated in late August through early October, northwest airlines the downtown opening period mainly concentrated in early occurrence peak in August to October, the northwest passage time mainly concentrated in the northern line opened in September. It is estimated that by the middle of the 21st century, the navigation period of the Northern Sea Route will be about 2–3 months, and by the end of the 21st century, it will be about 3–6 months. In different periods of a year, the environmental conditions of the navigable waters are greatly different, so the meteorological conditions of the navigable waters are also greatly different. Therefore, it is necessary to combine the actual conditions and take the actual meteorological environment of the Arctic route as the starting point to design meteorological routes. In recent years, the level of Arctic sea ice and weather forecasting among countries has improved, and cooperation and exchanges have expanded. However, there are still problems such as insufficient application of observation data, weak forecasting capacity in the central Arctic region and insufficient sharing of forecast information. In order to improve the reliability of Arctic sea ice and weather forecasting, models and methods such as high-resolution coupled ice-sea model, TOPAZ4 data assimilation system and the addition of Arctic radiosonde observation have been widely used. It improves the accuracy of maritime weather forecast and the feasibility and navigation safety of the Arctic weather route. Then based on the basic route, combined with the Arctic sea meteorological elements to design the initial weather route.

2.2. Air route optimization for meteorological air route

After completing the design of weather route, it is necessary to optimize the weather route. In recent years, the role and position of meteorological navigation in Marine navigation has become increasingly prominent, and many algorithms for optimal design of meteorological shipping routes have been proposed. In general, it can be divided into two categories, that is, traditional methods and intelligent methods. The traditional methods include isochron method, variational method and dynamic programming method. Intelligent methods include genetic algorithm, Dijkstra algorithm and ant colony algorithm. Among them, the dynamic programming method has a better effect in the optimal solution of multi-objective.

Dynamic programming method, the basic idea is similar to isochron method, its core is Bellman’s optimization principle. Dynamic programming is a mathematical method used to solve the optimization of multi-stage decision-making process in the optimization of ship meteorological route. Its characteristic is that it can transform an n-dimensional decision problem into several one-dimensional optimization problems, which can be solved one by one. (Fig 1)

![Multi-stage decision making](image)

Fig.1 Multi-stage decision making

The specific implementation steps are as follows: (Fig 2)

1) Dividing stages: Dividing stages is the first step to solve the multi-stage decision problem by using dynamic programming. After determining the characteristics of multi-stage, the process is divided into several interrelated stages in time or space sequence. To design good weather route every must make the time or distance into a position, compared with the ordinary shipping lane, more uncertainty factors in the arctic route, weather the weather forecast is not accurate enough, shortage of AIDS to navigation, therefore, in order to ensure the accuracy of optimization, interval time and position should be appropriate to shorten the distance.
(2) Correct selection of state variables: the selection of variables should not only accurately describe the process evolution but also meet the requirement of no after-effect, and the value of state variables at each stage can be determined. The existence of no aftereffect ensures that the optimization effect in the front stage of the ship will not have an impact on the ship, which improves the accuracy of the subsequent sections of the route. Similarly, only when the initial value of each stage is accurate can the route optimization accuracy be improved.

(3) Determine decision variables and allowable decision sets: Usually, key variables of the problem to be solved are selected as decision variables, and the value range of decision variables is given at the same time, that is, the allowable decision sets are determined.

(4) Determined the state transfer equation: according to the state variables and decision variables in K stage, write the state variables in K stage, and the state transfer equation should have a recursive relationship.

(5) Determining the stage index function and the optimal index function, and establishing the basic equation of dynamic programming: the stage index function refers to the return at the k stage, and the optimal index function refers to the optimal value of the return obtained from the state at the k stage to the end of the n stage, and finally write the basic equation of dynamic programming.

As the initial state is known and the decision of each section is a function of the state of this section, the state of each section through which the optimal strategy passes can be transformed segment by segment, thus the optimal route is determined and the optimization of meteorological route is completed.

![Dynamic programming method for optimization of meteorological routes](image)
2.3. Route assessment of Arctic routes
After the optimization of meteorological route is completed, it is necessary to evaluate the optimized route to prove the feasibility of the optimized route. Airline evaluation is a traditional concept. In the modern sense, it refers to the comprehensive evaluation of the safety, adaptability and economy of the designed route after the route design and optimization, so as to provide technical reference for the final decision of route choice. The feasibility evaluation of the planned route includes the navigation status of the ship and the information of the chart in the navigation area. Feasibility evaluation indexes are established according to the navigation status of ships. The maximum draft, tonnage, maximum speed and radius of the ship have a great influence on the judgment of the feasibility of the optimized Arctic shipping route. Judgment is made according to the chart information within the navigation area of the vessel: it mainly includes the identification of various navigational obstacles (such as clear reef, submerged reef, intertidal zone, sunken ship, restricted navigation zone, ice area, etc.) along the navigation area of the planned route and the acquisition of water depth at any geographic coordinate position at any scale level in the chart. Among them, the ice area has a great influence on the Arctic shipping route. When the proportion of floating ice covering on the sea is large, the ship will find it difficult to navigate or even lose its maneuverability.

Steps of route evaluation (Fig 3)
(1) Obtain navigation ship parameters (ship size, ship maximum speed, ship maximum draft, etc.) from ship database;
(2) Obtain the optimized meteorological route of the ship;
(3) In combination with (1) and (2), the possible navigation area of ships (a buffer zone considering ship parameters) with the planned route as the central axis is obtained, hereinafter referred to as the "navigation area";
(4) All the land and intertidal zones within the geographical range of the "navigation zone" are obtained, and whether these areas intersect with the "navigation zone" is judged one by one. If they intersect, it means that some of the "navigation zone" falls in the land or intertidal zone. It is concluded that the planned route is not feasible; Otherwise, proceed to Step (5);
(5) All restricted navigation areas (sea ice areas) within the geographical range of the "navigation zone" are obtained, and whether these areas intersect with the "navigation zone" one by one is judged. If they intersect, it means that some of the "navigation zone" falls within the restricted navigation zone, and the conclusion is drawn: the planned route is not feasible; Otherwise, proceed to Step (6);
(6) Obtain all the navigational obstacles in the geographical area across the Navigation Area, and determine one by one whether these obstacles fall within the Navigation Area, and if so conclude that the planned route is not feasible; Otherwise, proceed to Step (7);
(7) Get all the water depth values within the cross-geographical range of the "navigation zone" and compare them one by one with the safe draft of the ship. If there is a water depth that is lower than the maximum draft of the ship, the planned route is not feasible, otherwise it is feasible.

After the completion of the navigation assessment, the design of the Arctic route with high feasibility can be obtained.
3. **Solving Algorithm**

As can be seen from the above model, the design of the Arctic route is a programmed process. In the design of Arctic meteorological route, models and methods such as high-resolution ice-ocean coupling model, Topaz4 data assimilation system and Arctic radiosonde observation are used to obtain high precision oceanic meteorological forecast information. In the arctic weather route optimization using dynamic programming convert a n d decision problem into several one-dimensional optimization problems, due to the initial state of each dimension is known, and every decision is a function of the segment status, so the optimal strategy by piecewise transformation by state of the paragraphs, to determine the optimal route, completed the weather route optimization. In the evaluation of the Arctic meteorological route, the route is evaluated according to the information of various obstructions within the navigation area of the planned route identified and the water depth points at any geographic coordinates at any scale level obtained on the charts.

4. **Simulation calculation and result analysis**

Computer simulation technology can simulate optimized Arctic shipping routes. Computer simulation technology is a comprehensive technology which uses the achievements of computer science and technology to establish the model of the system to be simulated, and carries on the dynamic experiment to the model under some experimental conditions. It has the advantages of high efficiency, safety, less constraint by environmental conditions, changable time scale and so on. It has become an important tool for analysis, design, operation, evaluation and training systems (especially complex systems). Computer simulation technology can be used to calculate the similarity of the designed Arctic route and analyze the results. Therefore, the actual operational risks of shipping companies engaged in Arctic shipping routes can be reduced to the greatest extent through the simulation technology, and the reliability of the designed Arctic shipping routes can be fully demonstrated through the obtained simulation results.
5. Conclusion
Under the conditions of the same port of departure and port of destination, ships choose different routes and pass through different sea areas in the course of operation. In this paper, aiming at the optimal solution of ship's shortest sailing time and ship safety under different operating conditions, simulation experiments are carried out on the traditional shipping route and the designed Arctic meteorological shipping route respectively by using the method of computer simulation technology. Through the simulation results, the ship's shortest voyage time and navigation safety information under the two routes are analyzed, and the ship's operation condition is compared with the design, optimization and evaluation of the route with or without weather. The experimental results show that the route design and optimization of the Arctic meteorological route has certain advantages in many aspects.

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