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Multi-criteria approach to the problem of choosing optimal routes in the waters of the Northern Sea Route

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ABSTRACT

The article is devoted to the problem of choosing the optimal routes for large-capacity transport vessels in the waters of the Northern Sea Route. The relevance of the topic is associated with the requirements of implementation of the Comprehensive plan for the development of the Northern sea route to 2030 and development Strategy of the Russian Arctic up to 2035. The article assesses the current state of the Arctic transport system and the changes that have affected the composition and structure of the transport fleet, the duration of the navigation period, the construction of new Arctic ports and cargo terminals, the growth of sea cargo transportation, navigation, hydrographic and hydrometeorological and ice support for navigation. The results of an analytical review of scientific research devoted to solving problems of choosing optimal routes are presented. The analytical review allowed us to get an idea of the methods and approaches that are usually used in solving such problems. The solution, as a rule, is reduced to solving a one-criterion or two-criterion problem. When choosing the optimal routes for sea vessels, the solution is found mainly for one specific class of vessels. A more general solution based on a multi-criteria approach has been developed. As criteria, it is proposed to take into account the length of the routes, the time of transition, as well as the safety criteria associated with the possible landing of the vessel on a shoal or receiving ice damage. In the first case, when solving the problem, the influence of insufficient hydrographic knowledge of the terrain on the safety of navigation along the route was taken into account. Calculation formulas for calculating navigation safety indicators are obtained. The necessity of using the Pareto principle is justified. The results of testing the developed methodology are presented. The ways of further research are outlined.

KEY WORDS: Northern Sea Route; Shipping routes; Multi-criteria approach; Optimization criteria; Pareto principle.

INTRODUCTION

The Northern Sea Route (NSR) is an actively developing maritime transport system. It shows significant structural and quantitative changes. The share of large-capacity transport vessels, as well as vessels with the category of ice reinforcements Arc7, is increasing. The network of shipping routes is expanding. The area of the water area where year-round navigation is carried out is increasing. Construction of new ports and reconstruction of the existing port infrastructure is actively underway. Dredging works are carried out in some areas. A large-scale planned survey of the bottom relief on shallow sections of shipping routes is being carried out. In the waters of the NSR, there is a significant increase in the intensity of navigation. In 2020, the volume of cargo transportation in the water area increased to 33 million tons, which is 4.7% higher than in 2019. Experimental icebreaking and transport flights are being carried out in the Eastern sector of the NSR, with the aim of extending the navigation period to 9-10 months a year (Andreeva et al., 2019, Tezikov et al., 2021). On new shipping routes, the risk of accidents involving ground contact in shallow water (Afonin et al., 2017, 2019) and ice damage should be kept to a minimum. Finding the optimal route in conditions of shallow depths and solid ice is of great practical importance. The optimal route is understood as a route that meets the requirements of aviation safety, as well as the requirements imposed on the time of passage of the vessel along the route. A review of methods for finding optimal routes for sea vessels in work Reimer (2015), Topaj et al. (2019) and Dobrodeev et al. (2018) showed that all of them, as a rule, are based on solving two-criterion problems. The solution of the problem relates mainly to one specific type of vessel. It does not allow using the received solution for vessels of different types, differing in draft and ice cross-country ability. The purpose of this work is to develop a method for finding optimal routes, which allows us to take into account the length of the route, the time of transition, as well as the criteria for the safety of navigation of vessels in conditions of shallow depths, insufficient hydrographic knowledge of the bottom relief, difficult ice conditions and tightness of the fairway.

METHODS

The safety criteria depend on the ice class of the vessels, their draft and maneuverability characteristics, as well as on navigational - hydrographic, hydrometeorological and ice conditions (Kiiski et al., 2016). The search for the optimal route is proposed to be performed on the basis of solving a multi-criteria problem. The optimal routes include routes on which the navigation of ships, firstly, will be fundamentally possible, secondly, it will be safe, and in addition, it will take little time. The experience of Arctic shipping shows that the shortest route in Arctic waters is not always the fastest.

In general terms, the transit time along the route is determined by the expression:

$$T = \frac{l}{V}\,, \tag{1}$$

where T is the transition time; l is the length of the route; V is the ship's speed.
The speed of the vessel V is denoted as:

$$V = F \cdot V_0\,, \tag{2}$$

where $F = F\ (f_1,\ f_2,\ f_3)$ is the factor of navigation safety; V_0 is the speed of the ship at F=1; f_1 is the depth factor; f_2 is the ice factor; f_3 is the constraint factor.
In formula (2), the condition $F = 1$ is fulfilled when the influence of shallow depths, ice and tightness on the ship's speed is absent. From expression (2) it follows that at $F = 1$ the ship's speed takes the maximum value $V = V_0 \rightarrow max$. The transit time along the route in accordance with expression (1) takes the smallest value. The condition $F = 0$ is satisfied when at least one of the indicators f_1, f_2, f_3 takes zero value. In this case, the route for navigation of ships becomes unsuitable, the vessel completely loses its speed $V \rightarrow 0$, the transition time along the route tends to infinity $T \rightarrow \infty$. A complete loss of speed occurs when the characteristics of the vessel do not meet the safety requirements in the prevailing navigation conditions on the route. In this case, the route must be changed, which entails an increase in its length. There may be cases where the shortest routes have the greatest speed loss, while the longer routes may have minimal or no speed loss at all. Under these conditions, taking a longer route may be less dangerous than taking a shorter route. Of the many routes that are characterized by the same values of the indicator $F \neq 0$, the optimal route is the one that takes the minimum time. This condition is generally achieved by a special ratio of the

length of the route and the speed of the vessel on it.
The effect of the depth Z on the possible loss of speed of a vessel with a draft d is generally described by the relation:

$$f_1 = f\left(\frac{d}{Z}\right), \tag{3}$$

where $f_1 \in [0; 1]$.
At great depths, when $Z >> d$, the influence of the factor f_1 on the drop in the ship's speed is absent. Under such conditions, the form of the value of function (3) should tend to unity. At shallow depths, when $Z \leq d$, the influence of the factor f_1 on the drop in the ship's speed is maximal. In such cases, the value of function (3) must take zero value. From expression (3) it follows that on the same route the effect of depths on the speed drop depends on the ship's draft d. For vessels with shallow draft, the depths have less impact compared to vessels with larger draft.
Some parts of the NSR water area may be characterized by insufficient hydrographic knowledge of the bottom topography, which results in the fact that in the intervals between the depths on the navigation maps there can be local bottom uplifts that were not detected during the survey.
To take into account the hydrographic knowledge, it was proposed to correct the depths on the route by the correction Δ_L, the value of which depends on the details of the measurements performed and the morphometric characteristics of the bottom topography.
Taking into account the correction Δ_L, formula (3) takes the form:

$$f_1 = f\left(\frac{d}{Z - \Delta_L}\right). \tag{4}$$

In those areas where survey work was not carried out and there is no information about the depths, it is assumed that the value of the correction Δ_L is equal to the depth Z. With this assumption, function (4) should have such a form that the f_1 exponent becomes zero. The latter means that a route laid through an unexplored water area will be dangerous for any vessels.
In the surveyed areas, the value of the correction is calculated by the formula:

$$\Delta_L = k \cdot L. \tag{5}$$

where k is an indicator of vertical dissection of the bottom topography at the level of 95% availability; L is an indicator of the detail of the measurement.
The Δ_L correction takes on a zero value when the bottom topography is surveyed using multibeam echo sounders or other bottom survey tools that guarantee reliable detection and survey of all dangerous depths.
Studies (Afonin et al., 2017) have shown that for the water area of the NSR, the maximum value of the vertical dissection index at the level of 95% availability is 0.006. Taking this into account, the correction for hydrographic knowledge corresponding to an inter-haul distance of 500 m will be 1.5 m; the correction corresponding to an inter-halo distance of 2000 m is 6.0 m, and so on.
The effect of ice on the possible loss of speed of a vessel with icebreaking capacity h_c is generally described by the relation:

$$f_2 = f\left(\frac{h_f}{h_c}\right), \tag{6}$$

where $f_2 \in [0; 1]$; h_f is the actual ice thickness on the route.
For thin ice, when the condition $h_c > h_f$ is fulfilled, the ice influence indicator f_2 is within $0 < f_2 < 1$, the movement of the vessel along the route is possible. For thick ice, when $h_c \leq h_f$, then $f_2 = 0$, the passage of the vessel is impossible.
Vessels operating in the water area of the NSR have different categories of ice reinforcement and different ice possibility.
For this reason, the f_2 index for vessels with different ice possibility can have different values:

– if for vessels of group i and j the ice possibility indices are set by the inequality $h_{ci} > h_{cj}$, then the corresponding ice influence indicators are determined by the inequality $f_{2i} < f_{2j}$;
– if for vessels of group i and j the ice possibility indices are set by the inequality $h_{ci} < h_{cj}$, then the corresponding ice influence indices are determined by the inequality $f_{2i} > f_{2j}$.

The ice classes of ships and the value of their icebreaking capacity are established in the Rules of the Russian Maritime Register of Shipping.
The influence of the constraint factor on the possible loss of vessel speed is taken into account using the f_3 indicator:

$$f_3 = f\left(\frac{B_f}{B_0}\right), \tag{7}$$

where $f_3 \in [0; 1]$; B_f is the width of the ship's safe movement strip; B_0 is the width of the fairway.
Areas with cramped conditions are usually understood as water areas where the vessel is limited in its ability to maneuver due to proximity to the coast and other navigational hazards. Almost the entire water area of the NSR can be attributed to confined waters. Most of the routes of the NSR pass through shallow areas surrounded by numerous shoals and banks, as well as dangerous ice formations in the form of ice fields, hummocks, stamukhas and even icebergs.
Depending on the ratio of the width of the safe movement of the vessel and the width of the fairway, the following conditions may be met:

– if $B_0 > B_f$, then the indicator of the influence of constraint on the speed of the vessel is within $0 < f_3 < 1$, the movement of the vessel along the route is possible;
– if $B_0 < B_f$, then the indicator of the constraint of the route is zero, the passage of the vessel is impossible.

Taking into account the joint influence of external factors on the ship's speed, the safety factor F in general form can be represented as the product of three functions:

$$F = f_1\left(\frac{d}{Z - \Delta_L}\right) f_2\left(\frac{h_f}{h_c}\right) f_3\left(\frac{B_f}{B_0}\right), \tag{8}$$

Factor F in expression (8) affects the actual vessel speed V in formula (2).
If $F = 1$, then $V = V_0$. In this case, the influence of the factor on the speed is absent, which is characterized by the joint fulfillment of the following conditions: $B_f = B_0$; $h_f = 0$; $Z >> d$ and $L \rightarrow 0$.
If $F = 0$, then $V = 0$. In this case, the vessel on the route stops moving under the influence of at least one of the following conditions: $h_f \geq h_c$, or $d \geq Z - \Delta_L$, or $L \rightarrow \infty$, or $B_f \rightarrow 0$.
Taking into account expressions (1) and (8), the optimal route must satisfy the conditions:

$$\left.\begin{array}{r} T_{\text{опт}} = \min\{T\} \\ F_{\text{опт}} = \max\{F\} \\ F \neq 0 \end{array}\right\}, \tag{9}$$

In accordance with the Pareto principle (Jafaryeganeh et al., 2020), when choosing the optimal route, one should be guided by the following rules:

– out of the set of routes characterized by the same values of the indicator $F \neq 0$, the optimal route is the one along which the minimum time is spent;
– in the case when the travel time along several routes has the same minimum value, the route, the safety indicator of which has the greatest value, is taken as the optimal one.

RESULTS AND DISCUSSION

To illustrate the developed method for choosing the optimal route on the NSR, let us consider an example of finding the optimal route for vessels with the ice category Arc7, having a draft of 12 m and an icebreaking capacity of 1.7 m. The speed of the vessel in clear water V_0, in the absence of the influence of shallow water, is assumed to be 12 knots. The routes are located between borders A and B, and the distance between them in a straight line was equal to 200 miles. The depths on the straight line AB were about 50 m. The depths decreased with the distance in the southeast direction. We will assume that the underwater topography has been studied with a detail of 500 m. The ice thickness along a straight line connecting points A and B was 1.3 meters. With distance from this line in the southeast direction, the ice thickness decreased to 0.4 m. The constraint factor f_3 was not taken into account in the example, since the water area is of an open type. 12 routes were selected between points A and B. For each route, their parameters were determined, the values of which are given in the Table 1.

Table 1 – Parameters of the investigated routes in the water area of the NSR

№ routes, i	l, miles	Z, m	h, m	f_1	f_2	F	V	T
1	2	3	4	5	6	7	8	9
I	200	50	1.30	0.76	0.23	0.17	2.0	100
II	210	50	1.30	0.76	0.23	0.17	2.0	105
III	220	40	1.20	0.70	0.29	0.20	2.4	92
IV	230	30	1.10	0.60	0.35	0.21	2.5	92
V	240	30	1.00	0.60	0.41	0.25	3.0	80
VI	250	30	0.90	0.60	0.47	0.28	3.4	74
VII	260	30	0.80	0.60	0.53	0.32	3.8	68
VIII	270	24	0.60	0.50	0.64	0.32	3.8	71
IX	280	22	0.50	0.45	0.70	0.32	3.8	74
X	290	20	0.40	0.40	0.76	0.30	3.6	80
XI	300	18	0.40	0.33	0.76	0.25	3.0	100
XII	310	10	0.40	0	0.76	0	0	∞

In the Table 1:
column 1 - route numbers (I - XII);
column 2 - route length l in miles;
column 3 - depth Z on the route in meters;
column 4 - ice thickness h in meters;
column 5 - indicator f_1 of the effect of depth on the loss of speed;
column 6 - indicator f_2 of the influence of ice on the loss of speed;
column 7 - indicator of navigational safety of route F;
column 8 - the speed of the vessel V on the route in knots;
column 9 - transit time T on the route in hours.

CONCLUSIONS

The data given in Table 1 allow us to carry out a comparative assessment of the routes. Route I is the shortest. This route has the most significant effect of ice on speed reduction. In this case, the effect of depths on the loss of speed is of the least importance. The cumulative impact of external factors on the vessel leads to a decrease in speed on the route to 2.0 knots. The transition time is 100 hours. Route XI is 300 miles long, three times the length of Route I. Nevertheless, the travel times for both routes are the same due to the fact that the speed on route XI is 1 knot higher compared to route I. The longest crossing time, 105 hours, is spent on Route II, where the thickness and depths are the same as route I, but the length of route II is 10 miles longer than the length of route I. The fastest speed, 3.8 knots, is found on routes VII, VIII and IX. The shortest crossing time, 68 hours, was recorded on route VII. Route XII in terms of ice conditions is quite favorable, but in terms of depths it cannot be used for vessels with a draft of 12 m. As a result of the application of a multi-criteria approach of 12 routes, route VII was recognized as optimal in terms of safety and transit time. The route layout is shown in the Figure 1.

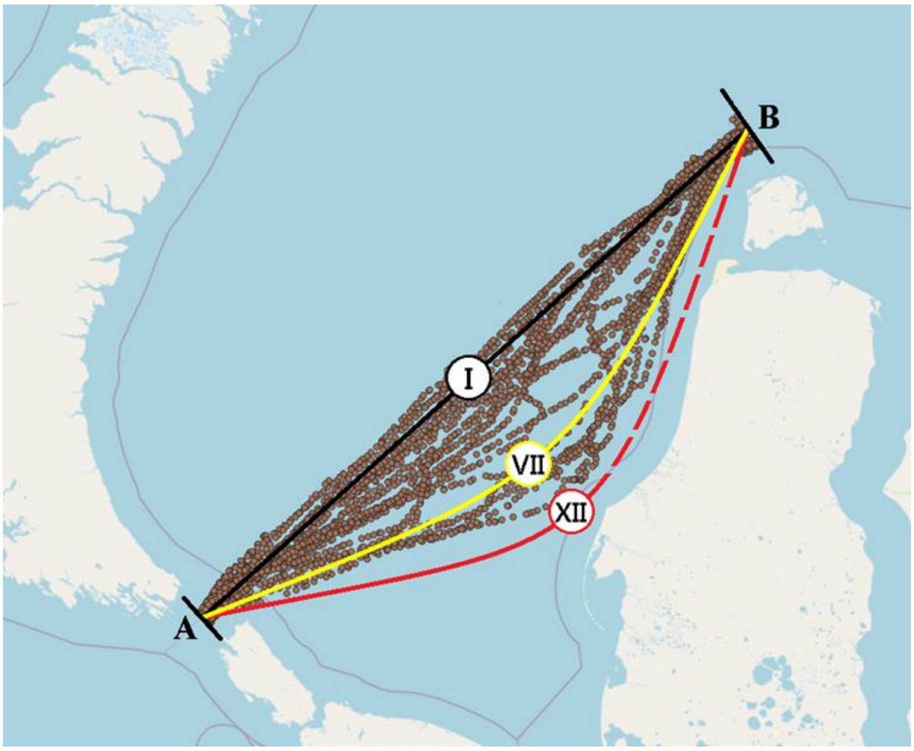

Figure 1 – The scheme of the investigated routes in the southwestern part of the Kara Sea (winter navigation)

The optimal route is highlighted in yellow on the route map (Figure 1). Route XII, which is prohibited for navigation by vessels of the accepted type, is highlighted in red.
In summer navigation, when there is no ice at the crossing between the borders A and B, ships move in a strip about 10 miles wide (Figure 2). The safety of vessel traffic on these courses remains high, and the transition time is close to the minimum time. The route with the minimum time value in Figure 2 is highlighted with a yellow line.

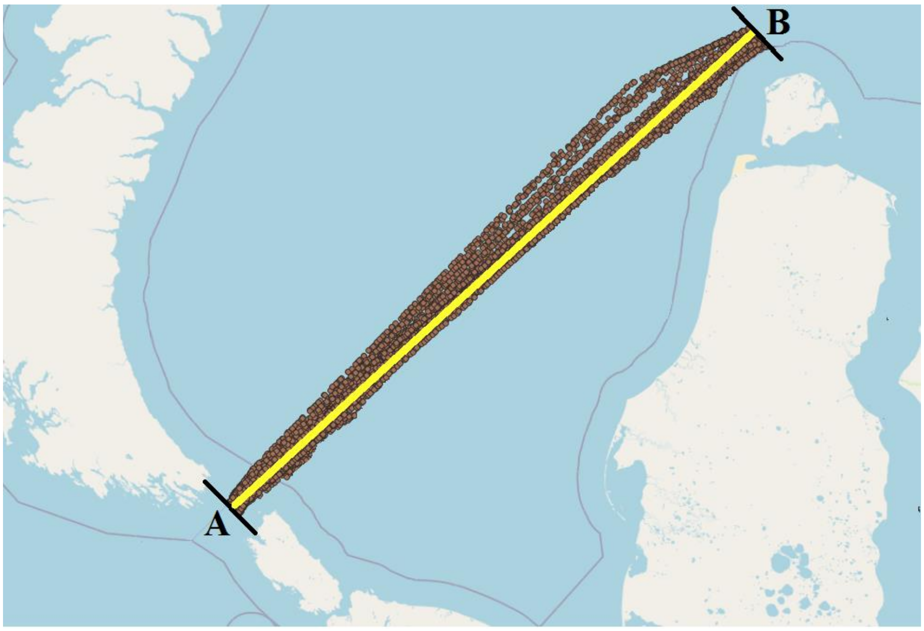

Figure 2 – The scheme of the investigated routes in the southwestern part of the Kara Sea (summer navigation)

The proposed method makes it possible to solve the problem of finding the optimal routes for ships in a complex navigational - hydrographic and ice situation. The accuracy and efficiency of solving the problem of choosing the optimal routes depends on the completeness and reliability of the initial information. Comparing the results obtained with the works of other authors (Lin et al., 2018), we can conclude about the practical applicability of the developed method for finding optimal routes in ice on the NSR. It is planned to test the method when choosing transit routes for transport vessels in the water area of the Northern Sea Route.

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