Simulation model for the North Sea Route transit time estimation

A L Kuznetsov¹, A V Kirichenko¹, V S Kiselev¹, A D Semenov²

¹Admiral Makarov State University of Maritime and Inland Shipping, Saint-Petersburg, Russia
²Yanino Logistics Park LLC, Saint-Petersburg, Russia

thunder1950@yandex.ru

Abstract. Today the Northern Sea Route attracts due attention of the international transport society. The Russian government has set a task to increase the cargo volumes transported via this way. There is an assumption that a substantial share of this amount would be the transit of the containerized cargo in both directions, Eastbound and Westbound. In these circumstances – since we speak about liner shipping and the maritime component of international intermodal transportation, there is a demand for scientifically proved methods of planning and prognoses of ice-breaker escort operations of transit caravans of merchant ships, both for selected legs and the whole route. This paper deals with the simulation model of the caravan of ships transiting the route leg by leg. The techniques proposed by this investigation enables to assess the random value – the time needed to pass along the Northern Sea Route. Simultaneously, the offered mechanisms permit to form the graphics of the movements along the parts of the route, which helps to make reliable forecasts for estimated passage times, estimated times for consolidation and dispersion of caravans, waiting times in the relay system of the movement along NSR. Eventually, these forecasts would form a base for the intermodal transportation chain.

1. Introduction

Today Russian Federation pays close attention to the development of its Arctic zone. There are program documents published which set the goals for improvements of the relevant transport system’s infrastructure, increasing of the cargo flows passing over the Northern Sea Route (NSR), including the transit ones [1], [2], [3], [4].

Some important steps were made in renovation of the icebreaker fleet operating in NSR aquatory with the aim to maintain the year-round navigation. In the same time, the questions of the rational utilization of this fleet, methods of optimal operational and tactical planning of massive transit transportation tasks remain studied insufficiently.

2. Literature review

In the initial stage of active exploration of the Arctic and establishing of the primary structure of the NSR were a lot of researches were conducted dedicated to the icebreaker escort operations’ planning and fulfillment. These works were exhaustive and nearly encyclopedic by their content and had very practical orientation [5], [6], [7]. Recommendation for good maritime practice leaned on accumulated experience and not on numerical techniques. Several modern researches deal with the organization of the icebreaker escort operation in narrow local areas, namely in Caspian water basin.
The study by M.A. Abdullatipov “Planning of icebreaker fleet operations in Caspian region” [8] offers a mathematical optimization model for operational planning aimed at minimizing total costs incurred by all transport process participants. The hypothesis of the study is that total costs of the merchant ships caused by their accumulation in the caravan formation point reduce with the number of the caravans while the icebreakers costs increase. The minimal value of the total costs enables to calculate the optimal number of ships. In the same time the reliability of the results received by the technique of mixed integer linear programming remains doubtful due to permanently changing values of stochastic values of parameters of icebreaker escort processes. The author takes into account local changing random variables specific to the conditions of icebreaker escort practice between Astrachan and Olja ports.

However, earlier more adequate methods, suggested by queueing theory, were applied to the problem of Caspian icebreakers activity planning. In [9] Temnikova A. A. considers two icebreakers as a queueing system. The effectiveness of system activity, which is defined by the average number of jobs in a queue, average waiting time in a queue, average number of jobs in the system and the average time in the system, were calculated with known time of winter navigation with heavy ice conditions, number of ships that must be served, the speed of icebreakers and distance between port of Astrakhan and ice edge of North Caspian sea. The author formulates the conclusion which is similar to the Abdullatipov’s: creation of additional service (utilization of two additional icebreakers) leads to the decrease of cargo ships waiting time behind the ice edge. Moreover, this leads to the reduction of caravan’s size that improves the economic issue.

Some papers are dedicated to definition of rational characteristics of icebreakers working in different locations.

In [10] Temnikova A. A. created an approach to calculate the value of ice resistance which is applied in the design of whole ship and in design of icebreakers propulsive complex. The paper also states some examples of this approach integration in practical issue of designing of propulsive complex of icebreakers that utilized at Volgo-Caspian canal and at North Caspian. The icebreakers resistance in solid ice, in ice brash and in the shallow was calculated in the case of special conditions of the district.

The earlier work [11] made by Tukova and Pichugina is dedicated to the design of icebreakers and calculation of their optimal characteristics from economical and operational point of view. The approach was considered as one of the solutions to the problem of icebreakers fleet provision in North Caspian. Authors also validated optimal characteristics of icebreakers working in North Caspian. These parameters are different to the ones operated in Volgo-Caspian channel.

In [12] Domanskaya shows the possibility to characterize the characteristics of light, medium and high ice conditions in different seas with the sum of frosty days. The paper also offers an analysis of shipping limits in different ice conditions for ships of various ice class. Author makes a fair conclusion that real problems of winter shipping in non-arctic seas are connected not with thickness of ice, but with the growth of the number and the dimensions of ships which use icebreakers assistance.

Most national researches are made in the case of Russian Federation Arctic region.

In [13] Peresipkin and Yakovlev form basic concept of NSR development. The concept implies that during complex development of NSR development and its commercial utilization, a self-supporting and economically effective Arctic sea transport system would be formed under government control by the 2010.

In the case of NSR transit traffic Tezikov, Andreeva and Isaulova considered a problem of large-capacity vessels safe movement on the routes with lack of information about NSR seabed relief [14]. Some papers (Kholopzev and others [15]) also consider prospects of ships movement in particular segments of NSR without icebreaking assistance (in the case of ships with ice class).

Thus, analysis of modern researches in the sphere of ice operations shows that optimization and simulation modeling are common approaches to solve different cases. At the same time, the earlier researches did not consider the problem of icebreakers fleet complex utilization planning in the case of mass ships traffic on the NSR.
3. Results and discussion

The analyses of planned ship flows, possible circulation legs of liner icebreaker rotation and ice environment states reveals the demand in setting and solving of exploitation tasks enabling to receive reliable estimations for several critically important indicators, like:
- estimated time of the caravan passing the total NSR distance and separated relay parts;
- estimated time of the caravan formation and dissolving;
- estimated time of the caravan waiting time in the relay succession icebreaker tasks under shuttle pattern of operations;
- average and seasonal NSR throughput capacity.

In its turn, this forecast forms the base for planning of total scheme of the transit container multimodal transportation over NSR. This study offers a method of estimation of the time needed to pass the NSR depending on different weather and ice conditions based on statistic data and Monte-Carlo techniques.

Under these assumptions, the whole NSR distance is considered to be constituted of several parts:

$$L = \bigcup_{k=1}^{K} l_k$$

As an example, this could be the most common (classical) division of the whole route into seven segments, as figure 1 shows.

![Figure 1. Northern Sea Routes](image)

Every segment is described by its distance $l_k$. The available statistical observations enable to assess the average speed of the ship travelling along every leg, which is mainly determined by the seasonal ice conditions. Accordingly, these ice conditions depend on the season of the year. Let us denote this mean value of the velocity on the segment $k$ in the navigation month $t$ as $v_{t,k}^k$.

Obviously, every mean speed of the kind $v_{t,k}^k$ is a stochastic value. Let us assume that as a result of statistical observations we know the distribution low of these variables characterized by their mean value $m_{t,k}$ and dispersion $d_{t,k}$, i.e. we know the integral probability curve:

$$F_{t,k}(m_{t,k}, d_{t,k}) = F_{t,k}(X) = P(v_{t,k}^k < X).$$

Figure 2 gives a sample of this dependency.
Figure 2. Example of the integral distribution of the stochastic value $v_t^k$

The existence of this dependency principally enables to generate random samples of the value distributed by this specific low. The easiest way to do it is to use the inverse function: if we have a random generator producing evenly distributed numbers belonging to the interval $[0,1]$ and denote is as $rand[0,1]$, then $F_{k,t}^{-1}(rand[0,1])$ is the value we look for.

The results of statistic observations could be represented by two rectangular matrixes: mean values $M = \| m_{t,k} \|_{12x7}$ and $D = \| d_{t,k} \|_{12x7}$, describing the speeds over the segment $k$ in different month $t$.

If a certain month of the year $t$ is selected, then the total elapsed time $T_t$ could be expressed as the sum

$$ T_t = \sum_{k=1}^{7} \frac{l_k}{v_{t,k}} $$

If a statistically sufficient number of tests were executed, then we could have a set of stochastic values of the variable $T_t$, and the traditional statistical processing of it could provide the assessment of distribution low of this value we are looking for.

Using this technique, we could gain the estimation of the random value – the total time of passing the NSR. Simultaneously, these two matrixes enable to build the movement graphics for every single leg of the route. In the first day the movement over the leg $k = 1$ the daily run will be $24 \cdot v_{t,1}$. When the ship will come out of the first lag’s distance and enter the second one, its daily run will be $24 \cdot v_{t,2}$ and so on. The correspondent graphic is shown by figure 3.
As one can see from this figure, as well as from the whole consideration above, this graphic reflects a realization of a random process. The multiple repetition of the simulation experiments enables to form the ensemble or family of these stochastic values (figure 4).

Obviously, the moment of arrival to the destination point (the moment of hitting the upper horizontal line) is a concrete value of the variable $T_t$. Figure 5 shows the distribution of this random value.
Figure 5. Distribution of the Northern Sea Route as a random value

The simulation results of the NSR passage time show a wide variety of the values. This variety becomes even wider if the simulation covers not one month, but the whole year, as figure 6 shows. Consequently, the reliability of the relevant logistic chain, which is described by the accuracy of arriving times, deteriorates.

The same variety show the times of passing separate segments of the total route. This leads to considerable losses at the organization of two-directional escort ice-breaker operations, when the ice breakers serve over the circle routes, since it is not possible to predict an exact time of arrival needed for the synchronization of both-way movements. As the result, sometime the icebreakers would be late the caravan escorts, and sometimes they would be late.

Figure 6. Seasonal variation of the Northern Sea Route passage
4. Conclusions
The research shows that organization transit container traffic in the NSR with linear icebreakers assistance is a stochastic process. That leads to the significant variation of forecasted operational parameters. As a result, the planned time of ships’ arriving can be completely different from the real one.

Suggested method based on the simulation model, allows to evaluate the probability density function of total NSR voyage time. At the same time, the method provides a possibility to form the timetables of ships' movement through all the NSR segments and of caravans’ transfer.

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