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Modeling Navigation, Ecologic and Economic Results of Planned Voyage of Ship on the Northern Sea Route

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ABSTRACT: Over the years, many publications have been published on planning ship's passage through the NSR and input and output data modeling. Results were not considered in terms of errors of modeled output data. Basic research for the years 2008 - 2020 was carried out in the study on opening and closing dates of ice-free transit corridor on the NSR and probable number of tariff zones where paid assistance of icebreakers would be required. Mathematical relationships of average values and probable errors of navigational, ecological and economic ship voyage performance were developed. For this purpose, partial derivatives of functions were used. The outcomes of the study have shown that changes of total average cost of vessel's transit voyage depends mostly on number of tariff zones where assistance of icebreakers is required. But navigation with icebreakers assistance ensures smaller standard deviation of total voyage time and thus more precise scheduling of ship's voyage timetable through the NSR. The higher probability of meeting requirements set by decision-maker when planning a long-term voyage of ship, the shorter time window for meeting these requirements. Outside the favorable time window, the navigational, ecological and economic results of voyage deteriorate very quickly.

1 INTRODUCTION

Since 1994 there has been a tendency in many countries other than the Russian Federation to show an increasing interest in usability the Northern Sea Route as an alternative shipping lane to traditional ones lanes connecting Europe with ports of the Far East via the Suez or Panama Canals. A number of simulation results of the navigation and economic performance of ship voyages by the NSR were published [9,10,11,12,19, 20,23, 28, 29]. Mulherin et al. [11] took into consideration statistical ice navigation conditions with the use of a cumulative distribution function of ice conditions. Kitagawa et al. [9] simulated average environmental conditions used that not reflected short-term environmental conditions changes. Smith and Stephenson [23] and Nam et al. [12] used very averaged data input organized in various ways. Wang et al. [28] approached multicriteria route planning including cost and risk. Zhang et al. [29] included meteorological risk, fuel consumption and time of voyage through the North Atlantic Ocean in the multicriteria algoritm using Pareto criteria. Matsuzawa et al. [10] and Pastusiak [19, 20] simulated ship's passage using already known ice conditions. All of them did not show input and output of simulated data errors. In the author's previous work [20], many examples of error values influencing the results of planning a ship's voyage in the regions of ice occurrence were presented. However, the impact of individual input data errors on the output error of the navigation and economic result of the voyage was not determined. The nature of the error and the probability for it was not specified (68.3%, 95.0% or 99.7%). Where different error values were given, it was not specified how the information on single input error could be used to evaluate the navigational or economic performance of a ship's voyage through ice covered areas [20]. Pruyn [22] analyzed conclusions coming from many publications and stated that most of them expected smooth navigation through the NSR without delays for inspections at the initial ports, without waiting for the convoy and without waiting for good environmental conditions. This author considered the need of icebreakers assistance as important cost building and potential elongation of voyage time factor. Due to above, in the present work possible use of icebreakers assistance was taken as a main problem for analysis.

In order to make rational decisions, one needs not only information about average values but also about their error values. It was assumed that the assessment of the navigational (time, date), ecological (used fuel producing CO2 and Greenhouse Gas) and economic performance (total cost of a voyage) should be based on more balanced criteria than pessimism or optimism of the decision maker. Modeling the ecological performance can be used to search for the methods to reduce CO2 and Greenhouse Gas production by improving the planning of ship operations. This work highlights possibility of using the mean error of the mathematical function instead of several data input errors to calculate the navigational, ecological and economic performance of the "long-term", it means at least three month period planned voyage, together with the determination of the uncertainty range well in advance of beginning of the voyage (Estimated Time of Departure ETD).

The aim of the study was to develop a method for long-time planning navigation, ecological and economic results of transit voyages and scheduling voyages through the Northern Sea Route (NSR) where ice may be encountered. Navigational results were based on length of route, speed of ship on selected sections of route, total voyage time, date of beginning of voyage at the port of departure and date of end of the voyage at the port of destination. Economic results of the voyage included the costs of fuel, charter, icebreaker assistance on selected sections of the route and total cost of entire voyage. Ecological results were presented by fossil fuel consumption. Final results of simulation involved average values and standard deviation. The study has shown that the number of tariff zones requiring icebreaking assistance has the greatest impact on performance of planned ship voyage.

2 RESEARCH METHOD

The first general principle was adopted, according to the ISM Code [21], that the model of navigational, ecological and economic performance of long-term voyage planning should be simple and transparent, and the results ready for direct implementation in the decision-making process. The International Maritime Organization [8] recommends that a voyage plan should include information on the accuracy and quality of each of the used electronic navigational charts, accuracy of ship position and reasonable accuracy of the timetable of voyage plan. A voyage plan should also determine impact of the above-mentioned accuracy and quality of data on the safety of navigation [8]. Following this recommendation as a second general principle, the inaccuracies of data input affecting the process of planning and scheduling, and navigational, ecological and economic performance of voyage on the NSR, were taken into consideration and worked out in this study. Taking into account the statistical mean values, errors and uncertainty ranges should be helpful for the substantive assessment of the profitability of the project concerning the activation of seasonal navigation with ships without ice reinforcements through the NSR (transit navigation) or for destination navigation (to / from a port located inside the NSR) as a link of intermodal transport connecting the European and Far East ports with ports located deep in Siberian rivers.

The input and output data should be measurable to allow comparisons to be made. This is to enable evaluation and objective decision to be made. These data should therefore be presented using historical information, i.e. statistical values - mean values and theirs errors values. Data processing systems transforming input data into output data should base on mathematical formulas only. Previously mentioned concept "long-term" should be understood as a time advance of at least 3 months, when only historical, i.e. statistical information, is available to voyage planners.

The aim of this research is to map the phenomena occurring in real conditions and play an important role in long-term planning of transit voyages of ships in the regions of ice existence on the Northern Sea Route. Therefore, there is a need to design selected fragments of the studied reality. It was assumed that selected navigational and economic results of ship's voyage are significant elements of reality. Navigational results are based on length of route, speed of ship on selected sections of route, total voyage time, date of beginning of voyage (Estimated Time of Departure ETD) and date of end of the voyage (Estimated Time of Arrival ETA) at nodal points, i.e. the port of departure and port of destination. It has been assumed that such ports will be places where safety clearances of ships are carried out before commence of voyage on the NSR. It will be the port of Murmansk roads on the western side of the NSR and the port of Provideniya roads on the eastern side. The study considered the case of a ship passage from west to east. Economic results of the voyage include the costs of fuel, charter, icebreaker assistance on selected sections of the route, if ice conditions on route require it, and total cost of entire voyage. Due to the involvement of ship-operators in counteracting climate change, attention was paid to fuel consumption as a factor generating greenhouse gases. Ships were assumed to be assisted only by nuclear powered icebreakers. Nuclear energy generation has near to zero green-house gas emissions in the energy generation phase [2, 3]. Under the EU Taxonomy Regulation, certain nuclear activities that fulfil nuclear and environmental safety requirements can be added to those already covered by the first Delegated Act as transitional activities to contribute to the transition to climate neutrality [2, 3]. From this point of view, nuclear propulsion assumed is an ecological propulsion. In such a situation, possible assistance of icebreakers during ship's voyage was not added to environmental costs of ship's voyage. Other components of planning were considered irrelevant to study of reality and were omitted in the study. For this reason, possibility of ship awaiting possible improvement in ice navigation conditions was omitted in considerations.

The study used ice concentration maps in simplified Marginal Ice Zone scale [13]. The work concerns navigation on ships without ice reinforcements, which should avoid areas of ice occurrence. It will be sufficient to know edges of the lowest ice concentration. These maps contain this information. They are published within 24 hours. This is relatively high frequency of publication compared to other published ice maps. It ensures minimization of influence of ice drift on location of its edges used in the research.

The work was based on historical, it means statistical data. All statistical results are affected by errors. Therefore, there was the need to determine the values of possible deviations from the mean values. This concerned input data, output data and ranges of uncertainty. To define them, mathematical formulas reflecting the processes taking place and errors of these formulas were obtained by means of derivatives of functions.

3 MODELING THE RESULTS OF NAVIGATIONAL, ECOLOGICAL AND ECONOMIC OF A SHIP VOYAGE

The first navigation information is date and time of beginning of voyage (ETD). Date of opening transit corridor through the whole NSR in the most difficult to overcome chocking zone TCZ for defined ice class of ships determines date of departure of a ship from the port of departure T0, i.e. the date of the beginning of voyage (ETD). The chocking zone is area on the NSR which opens the latest and closes the first. Date T0 can be determined with Equation 1. Variables included in the formula are independent. Statistical values will be required for distance from departure port to the edge of the first tariff zone at the west side of the NSR DOUT1 and for distance from the edge of first tariff zone at the west side of the NSR to the mean location of the chocking zone DIND1 and the ship speed in these sections. It was assumed that a ship commence its voyage when ice conditions between port of departure and chocking zone allow for independent navigation of this ship.

$$T_0 = T_{CZ} - \frac{D_{OUT1}}{24 \cdot V_{FA}} - \frac{D_{IND1}}{24 \cdot V_{IND}} \quad (1)$$

The second navigation information is total voyage time between the port of origin and port of destination TTTL (Equation 2). To make calculations, it will be necessary to determine statistical values for the length route segments of DOUT1 on the western side of the NSR, DOUT2 on the eastern side of the NSR and the lengths of route segments in individual tariff zones. The latter may apply to independent navigation of a ship on the section of DIND length or navigation with the icebreakers assistance along the section of DIB length, which is payable according to the NSR Administration tariff [4]. Specified ship speeds VFA for navigation outside ice areas, VIND for independent navigation and VIB for navigation assisted by the icebreakers correspond to ice navigation conditions. The maximum number of tariff zones is 7 [5]. What is needed is knowledge of the number of tariff zones requiring the assistance of icebreakers because of the ice conditions occurring within the Julian day of the year.

$$T_{END} = \left(T_{CZ} - \frac{D_{OUT1}}{24 \cdot V_{FA}} - \frac{D_{IND1}}{24 \cdot V_{IND}} \right) + \left(\frac{D_{OUT1}}{24 \cdot V_{FA}} + \frac{k \cdot D_{IB}}{24 \cdot V_{IB}} + \frac{(n-k) \cdot D_{IND}}{24 \cdot V_{IND}} + \frac{D_{OUT2}}{24 \cdot V_{FA}} \right) \quad (2)$$

After adding the time of ETA (date) of the beginning of the voyage T0 and the total time of the voyage TTTL, the time (date) of the end of voyage TEND (ETA) at the destination port is obtained (Equation 3).

$$T_{END} = \left(T_{CZ} - \frac{D_{OUT1}}{24 \cdot V_{FA}} - \frac{D_{IND1}}{24 \cdot V_{IND}} \right) + \left(\frac{D_{OUT1}}{24 \cdot V_{FA}} + \frac{k \cdot D_{IB}}{24 \cdot V_{IB}} + \frac{(n-k) \cdot D_{IND}}{24 \cdot V_{IND}} + \frac{D_{OUT2}}{24 \cdot V_{FA}} \right) \quad (3)$$

The fuel consumption was adopted as ecological result of the planned voyage. In addition to the previously specified factors, it is necessary to know ship's daily fuel consumption under way related to areas where ice not exists CFA, in areas where ice exists but the ship proceed without assistance of icebreakers CIND or the ship proceed with assistance of icebreakers CIB (Equation 4). After adding up the costs of charter, fuel used and paid icebreakers services, the total cost CTTL of the ship's voyage through the NSR was obtained (Equation 5).

$$FC = \frac{D_{OUT1}}{24 \cdot V_{FA}} \cdot C_{FA} + \frac{k \cdot D_{IB}}{24 \cdot V_{IB}} \cdot C_{IND} + \frac{(n-k) \cdot D_{IND}}{24 \cdot V_{IND}} \cdot C_{IB} + \frac{D_{OUT2}}{24 \cdot V_{FA}} \cdot C_{FA} \quad (4)$$

$$C_{TTL} = T_{TTL} \cdot C_{CH1} + FC \cdot C_{F1} + C_T \cdot R \cdot GT \quad (5)$$

Cost of assistance of icebreakers CT in Equation 5 is published by the NSR Administration [5] for ships of particular ranges of Gross Register Tonnage (GRT). It depends on number of the tariff zones where a ship require assistance of icebreakers due to ice navigation conditions existing there. For the ships in the range from 40,000 till 100,000 GRT without ice strengthenings (steel hull, no ice class) particular tariff points of CT for tariff zones 1-6 are lying on the line presented by Equation 6 (coefficient of determination R2 = 1). It is representing tariff in Russian Rubles per unit of the ship's Gross Tonnage.

$$C_T = 89.369 \cdot k + 357.47 \quad (6)$$

For defined rate of Russian Rubel R (1 RUB = 0.0136 USD at 01.09.2020 [24]) and PANAMAX class ship tonnage 38,500 GT the Equation 5 can be transformed into Equation 7.

$$C_{TTL} = T_{TTL} \cdot C_{CH1} + FC \cdot C_{F1} + GT \cdot R \cdot (89.369 \cdot k + 357.47) \quad (7)$$

A significant source of uncertainty for all decision factors is variability of beginning date of entire transit corridor to be opened for ice-free navigation TCZ. Then the number of tariff zones requiring assistance of icebreakers is equal to 0 (k=0). The geographic location of the chocking zone is also variable [16, 20]. This is where the transit corridor opens at the latest and closes at the earliest [18]. These variations can be determined by the standard deviation σ for 1M (i.e. 1 · σ), 2M (i.e. 2 · σ), or 3M (i.e. 3 · σ). The current IMO requirements for defining the value of navigational errors at sea apply to 2M (double standard deviation σ).

In all the above relationships (Equations 1-7) there are numerous components of uncertainty. The question is, on the basis of which factor the person in charge of a long-term voyage planning (3-12 months in advance) should make his decisions. There is a problem of multi-criteria decision making. Using different single input and output data for a decision system leads to the calculation of different results, of different nature and thus difficult to compare. However, it is possible to reduce multi-criteria. This can be done using the method of determining the mean errors of functions defined by the formulas (Equation 1-7). Then only the basic navigational, ecological and economic criteria for making decisions will be maintained. To do this, one performs the differentiation, i.e. calculation of derivatives [25] of equations 1-5 and 7 with respect to the components of equations with errors [6, 26]. Thus, the formulas (Equation 8-12) are obtained, which define the mean values of errors of functions for the mean values (Equations 1-5 and 7). In order to use the formulas 1-12, it is necessary to know the mean values and the standard deviation of all variables included in the formulas above. Based on the mean values and their errors (standard deviation), ranges of decisive outputs can be determined.

$$T_0' = \pm\sqrt[2]{\left(\frac{1}{24\cdot V_{FA}}\right)^2\cdot m_{D_{OUT1}}^2+\left(\frac{-D_{OUT1}}{24\cdot V_{FA}^2}\right)^2\cdot m_{V_{FA}}^2+\left(\frac{1}{24\cdot V_{IND}}\right)^2\cdot m_{D_{IND1}}^2+\left(\frac{-D_{IND1}}{24\cdot V_{IND}^2}\right)^2\cdot m_{V_{IND}}^2} \quad (8)$$

$$T_{TTL}' = \pm\sqrt[2]{\begin{aligned}&\left(\frac{1}{24\cdot V_{FA}}\right)^2\cdot m_{D_{OUT1}}^2+\left(\frac{-D_{OUT1}}{24\cdot V_{FA}^2}\right)^2\cdot m_{V_{FA}}^2+\left(\frac{k}{24\cdot V_{IB}}\right)^2\cdot m_{D_{IB}}^2+\left(\frac{-k\cdot D_{IB}}{24\cdot V_{IB}^2}\right)^2\cdot m_{V_{IB}}^2+\left(\frac{n-k}{24\cdot V_{IND}}\right)^2\cdot m_{D_{IND}}^2+\\&+\left(\frac{-(n-k)\cdot D_{IND}}{24\cdot V_{IND}^2}\right)^2\cdot m_{V_{IND}}^2+\left(\frac{1}{24\cdot V_{FA}}\right)^2\cdot m_{D_{OUT2}}^2+\left(\frac{-D_{OUT2}}{24\cdot V_{FA}^2}\right)^2\cdot m_{V_{FA}}^2+\left(\frac{D_{IB}}{24\cdot V_{IB}}-\frac{D_{IND}}{24\cdot V_{IND}}\right)^2\cdot m_k^2\end{aligned}} \quad (9)$$

$$T_{END}' = \pm\sqrt[2]{\begin{aligned}&\left(\frac{1}{24\cdot V_{FA}}\right)^2\cdot m_{D_{OUT1}}^2+\left(\frac{-D_{OUT1}}{24\cdot V_{FA}^2}\right)^2\cdot m_{V_{FA}}^2+\left(\frac{1}{24\cdot V_{IND}}\right)^2\cdot m_{D_{IND1}}^2+\left(\frac{-D_{IND1}}{24\cdot V_{IND}^2}\right)^2\cdot m_{V_{IND}}^2+\left(\frac{1}{24\cdot V_{FA}}\right)^2\cdot m_{D_{OUT1}}^2+\\&+\left(\frac{-D_{OUT1}}{24\cdot V_{FA}^2}\right)^2\cdot m_{V_{FA}}^2+\left(\frac{k}{24\cdot V_{IB}}\right)^2\cdot m_{D_{IB}}^2+\left(\frac{-k\cdot D_{IB}}{24\cdot V_{IB}^2}\right)^2\cdot m_{V_{IB}}^2+\left(\frac{n-k}{24\cdot V_{IND}}\right)^2\cdot m_{D_{IND}}^2+\left(\frac{-(n-k)\cdot D_{IND}}{24\cdot V_{IND}^2}\right)^2\cdot m_{V_{IND}}^2+\\&+\left(\frac{1}{24\cdot V_{FA}}\right)^2\cdot m_{D_{OUT2}}^2+\left(\frac{-D_{OUT2}}{24\cdot V_{FA}^2}\right)^2\cdot m_{V_{FA}}^2+\left(\frac{D_{IB}}{24\cdot V_{IB}}-\frac{D_{IND}}{24\cdot V_{IND}}\right)^2\cdot m_k^2\end{aligned}} \quad (10)$$

$$m_{FC} = \pm\sqrt[2]{\begin{aligned}&\left(\frac{C_{FA}}{24\cdot V_{FA}}\right)^2\cdot m_{D_{OUT1}}^2+\left(\frac{-D_{OUT1}\cdot C_{FA}}{24\cdot V_{FA}^2}\right)^2\cdot m_{V_{FA}}^2+\left(\frac{D_{OUT1}}{24\cdot V_{FA}}\right)^2\cdot m_{C_{FA}}^2+\left(\frac{k\cdot C_{IB}}{24\cdot V_{IB}}\right)^2\cdot m_{D_{IND}}^2+\left(\frac{-k\cdot D_{IB}\cdot C_{IB}}{24\cdot V_{IB}^2}\right)^2\cdot m_{V_{IB}}^2+\\&+\left(\frac{k\cdot D_{IB}}{24\cdot V_{IB}}\right)^2\cdot m_{C_{IB}}^2+\left(\frac{(n-k)\cdot C_{IND}}{24\cdot V_{IND}}\right)^2\cdot m_{D_{IND}}^2+\left(\frac{-(n-k)\cdot D_{IND}\cdot C_{IND}}{24\cdot V_{IND}^2}\right)^2\cdot m_{V_{IND}}^2+\left(\frac{(n-k)\cdot D_{IND}}{24\cdot V_{IND}}\right)^2\cdot m_{C_{IND}}^2+\\&+\left(\frac{C_{FA}}{24\cdot V_{FA}}\right)^2\cdot m_{D_{OUT2}}^2+\left(\frac{-D_{OUT2}\cdot C_{FA}}{24\cdot V_{FA}^2}\right)^2\cdot m_{V_{FA}}^2+\left(\frac{D_{OUT2}}{24\cdot V_{FA}}\right)^2\cdot m_{C_{FA}}^2+\left(\frac{D_{IB}\cdot C_{IB}}{24\cdot V_{IB}}-\frac{D_{IND}\cdot C_{IND}}{24\cdot V_{IND}}\right)^2\cdot m_k^2\end{aligned}} \quad (10)$$

$$C_{TTL}' = \pm\sqrt[2]{C_{CH1}^2\cdot m_{T_{TTL}}^2+C_{F1}^2\cdot m_{FC}^2+(89.369\cdot GT\cdot R)^2\cdot m_k^2} \quad (11)$$

4 INPUT VARIABLES FOR THE MODELS

Long-term planning in advance from 3 to 12 months and more is necessarily based on historical or statistical data. It has been noted that main source of uncertainty at long-term voyage planning stage is date of opening transit corridor for navigation permissible for the specific ice class of ship, voyage time through the NSR and in particular additional costs of icebreaker assistance services. These costs of icebreakers services are rising discretely according to the number of tariff zones where ice conditions require a ship to use icebreakers assistance.

Responsible persons in the offices must take into account a number of factors when making long-term decisions related to planning of cargo transport by sea through the NSR. Earlier in the work, they were divided into navigational, ecological and economic factors. Navigational factors are length of route, date of beginning and end of voyage, time of voyage, ice class of ship and speed of ship under certain ice conditions. Ecological factors are type of fuel and fuel consumption along the entire route. The economic factors are cost of fuel consumed, charter cost for entire voyage and cost of tariffs for required icebreakers assistance. They can be determined using mathematical relationships. To use the formulas for average values (Equations 1-7) and to determine the uncertainty ranges (Equations 8-12), the standard deviation value of all variables included in the above formulas should be determined. Some of them require more extensive research. They are presented below.

4.1 *Dates of beginning and end of independent navigation and with icebreaker support*

Main criterion for navigation in areas where ice exists is routing through the lightest ice conditions. These lightest ice conditions on the NSR exist when an uninterrupted transit corridor is created along the entire NSR completely free of ice. For the long-term planning of a ship's voyage, it is important to know the opening and closing dates of such corridor. For this purpose, an analysis of the NIC MIZ ice maps was performed [13] for the period from 2008 to 2020. The number of tariff zones in which ship has to use services of icebreakers increases the cost of voyage by leaps and bounds, significantly affecting the economic result of the planned voyage of the ship. For this reason, it was decided to use same ice maps to determine number of tariff zones with ice before opening and after closure of ice-free transit corridor.

Earlier in the work has been noted that main uncertainties in long-term voyage planning are date when the NSR ice-free transit zone opens and closes, distance from port of departure to the chocking zone, which usually opens the latest, and the distance from port of departure on voyage to the chocking zone. As the research concerns a voyage from west to east, Murmansk was chosen as port of departure. Changes over time in number of tariff zones requiring (or not) use of paid icebreaker services for western and eastern parts of the NSR and changes over time for opening and closing of ice-free transit corridor are shown in Figures 1 and 2.

The graphs show that results for the opening of transit corridor (beginning of voyage) are consistent on both sides - west and east (Figure1). When planning the date of arrival of the ship at the zone blocking transit corridor for the longest time ("chocking zone" on the NSR) on basis of trend line for one tariff zone (red dash line), there is a high probability of not incurring charges for two or more tariff zones (blue, green or magenta lines) requiring assistance of icebreakers. When planning ship's arrival date to "chocking zone" on the NSR on basis of trend line for two tariff zones (blue dash line), there is very high probability of not incurring charges for three or more tariff zones requiring icebreaker assistance (green or magenta lines).

Planning ship's passage at chocking place on the NSR based on trend line for no tariff zones requiring icebreaker services, it is highly likely to incur charges for one tariff zone (red line) and a little likely to incur charges for two tariff zones (blue line).

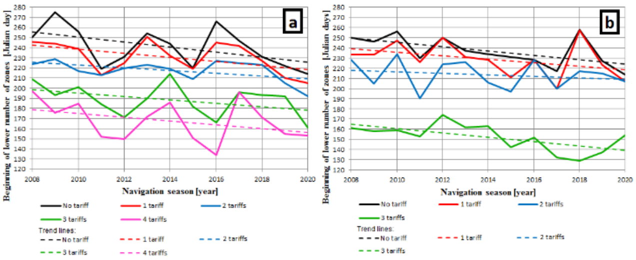

Figure 1. Number of tariff zones to be paid from given day foreward (and after that day) when opening transit corridor: (a) in western part of the NSR; (b) in eastern part of the NSR.

When planning date for the ship to pass through zone that blocks transit corridor at end of summer navigation season (Figure 2) on basis of trend line for three tariff zones (blue dash line), there is a high probability not to pay for four or more tariff zones requiring icebreaker assistance (green or magenta lines). Planning ship's passage at chocking zone on the NSR based on trend line for no tariff zones requiring icebreaker services, it is highly likely that ship will incur charges for one or two tariff zones (red and / or blue lines).

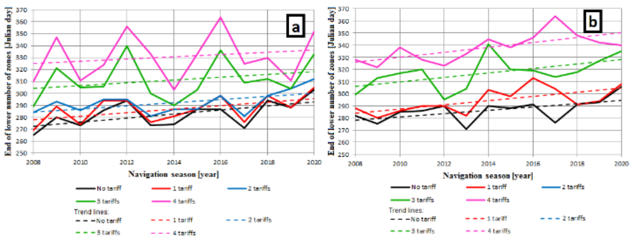

Figure 2. Number of tariff zones to be paid from specified day backward (and before that day): (a) during transit corridor closing in western part of the NSR; (b) during transit corridor closing in eastern part of the NSR.

Graphs in Figures 1 and 2 do not illustrate complex phenomena occurring. Information obtained on their basis does not constitute enough synthetic assessment of situation for purposes of making decisions. In that case, in next step, above relationships were analyzed. Time span of the navigation season (number of days) and the number of tariffs to be paid for required icebreakers assistance with theirs probability were found. The graph of average dates of changes in number of tariff zones requiring icebreaker assistance along the entire NSR was obtained, resulting from 2008-2020 with probability of occurence 68.3% (Figure 3). The x axis on this and next Figures is related to day of the year when a ship arrives at the chocking zone.

Standard deviation of date when change number of tariffs occurred is ± 11.9 days for range from 0 to 7 tariff zones. For the range from 0 to 5 tariff zones requiring icebreaker assistance, standard deviation for determining number of zones is ± 11.2 days. Average day of opened ice-free corridor is 264 (Julian day) with standard deviation ±7.4 days. Edges of zero number of tariffs are average dates of ice-free time window for the whole NSR. The averaged data set approximated with polynominal function of 5th degree (Equation 13). Coefficient of determination R2 is 0.9870. The only 4 tariff zones existing simultaneously are expected maximal value of tariffs to be analyzed. It is because the associated 30 days before opening of ice-free corridor and 30 days after closing ice-free corridor ice conditions existing on the NSR are too severe for ships without ice strengthenings – both for independent navigation and with assistance of icebreakers.

As a result of use of statistical relationships, it is possible to predict required day of arrival to the chocking zone on the NSR well in advance, more than 3 months before the commence of voyage occurs. That is, when reliable forecasts based on current hydrological and meteorological information cannot be expected yet.

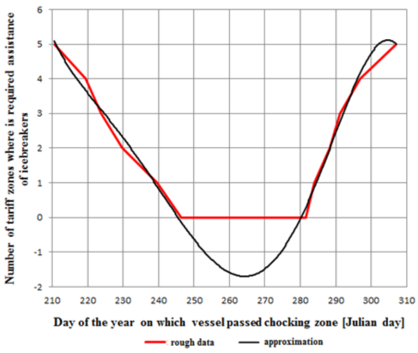

Figure 3. Number of expected tariff zones to be paid for icebreakers services on the whole NSR.

$$k=-2.60985\cdot10^{-9}\cdot T_{CZ}^{5}+3.03634\cdot10^{-6}\cdot T_{CZ}^{4}-0.00137753\cdot T_{CZ}^{3}+ \\ +0.304823\cdot T_{CZ}^{2}-32.9934\cdot T_{CZ}+1408.78 \tag{13}$$

It was assumed that the formula is valid for the number of tariff zones from null to 4. If the ice conditions on the NSR do not allow the ship to independently navigate more than four areas of tariff zones, it is assumed that ice conditions existing before and after number of days related to designed number of four tariffs are inaccessible for ships without ice strengthenings. Standard deviation of expected number of tariffs to be paid for required icebreakers assistance m_k is represented by Equation 14.

$$m_k=\pm\sqrt{\left(\begin{array}{c}-13.04925\cdot10^{-9}\cdot T_{CZ}^{4}+12.14536\cdot10^{-6}\cdot T_{CZ}^{3}-0.00413259\cdot T_{CZ}^{2}\\+0.609646\cdot T_{CZ}-32.9934\end{array}\right)^{2}\cdot\left(m_{TCZ}\right)^{2}} \tag{14}$$

4.2 *Time required to arrive from port of departure to the chocking zone*

If the ship arrives too early at the chocking zone, it will have to wait for ice conditions to improve and / or use expensive icebreakers services in one or more tariff zones. In this study, it was assumed that ship will not wait for improvement of hydrological conditions, but will use paid icebreakers assistance services in as many tariff zones as ice situation requires. Both waiting for ice conditions to improve and use of icebreakers are causing additional voyage costs.

It is therefore important to determine statistical location of chocking zone and hence length of route from origin port to chocking zone. In order to plan ship's voyage from west to east through the NSR, distances of center chocking zone from starting port (in our case, Murmansk) were determined for navigation seasons from 2008 to 2020. Found average value increased by standard deviation σ equal 2,221 nm, average value equal 1,709 nm, average value reduced by standard deviation σ equal 1196 nm, standard deviation σ equal 512 nm and also 1st quartile equal 1,384 nm, Median 1,547 nm and 3rd quartile equal 2,056 nm (Figure 4). Figure 4 shows that the vast majority of the chocking zones of summer navigation period in the years 2008-2020 were located close to Vilkitsky Strait (Mys Chelyuskin) at Kara Sea and Laptev Sea. The only clear anomaly was in 2012. Then chocking zone was located at Wrangel Island on New Siberian Sea. Based on known length of route from port of departure to chocking zone and speed of a ship, it is possible to calculate time needed to cover this part of route and date of commencement of voyage at the port of departure. It should be noted so appointed distances in between port of Murmansk roads and the Chocking Zone they do not apply to the route of the ship sailing straight ahead, but to the route that resulted from the circumstances of the ice navigation conditions. For this reason, the geographic location of the middle of the Chocking Zone (ice barrier) is better reflected by average geographic longitude of locations of these barriers along most frequently available route through the NSR. This gives in approximation average equal 120°E, standard deviation ±27.6°, median 109°E, 1st quartile 100°E and 3rd quartile 151°E.

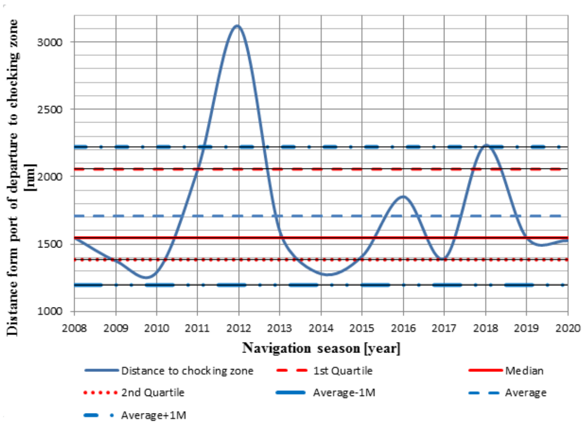

Figure 4. Distance from the port of departure (Murmansk) to chocking zone.

4.3 *Speed of the ship and daily fuel consumption*

In order to determine statistical values of speed for ships without ice strengthening passing through the NSR during independent voyage and with assistance of icebreaker an analysis was carried out based on navigation permits for the NSR issued by the NSR Administration [14] and daily reports produced by the above-mentioned ships during their voyage in 2016 [15]. In order to determine speed of the ship and fuel consumption outside areas of ice occurrence and fuel consumption in areas of ice occurrence, relationships developed in author's earlier work were used [17, 21]. Statistical results are summarized in Table 1.

Table 1. Speed and fuel consumption of PANAMAX type ship. Compiled by author based on [14, 15, 16, 20].

Component	Waters outside the NSR	Waters inside the NSR; independent voyage	Waters inside the NSR; voyage with assistance of icebreakers
Speed [kn]	13.70	10.70	9.14
St. dev. Of speed [kn]	0.33	2.23	1.86
Daily fuel consumption [mt/day]	31.7	34.2	39.3
St. dev. of consumption [mt/day]	1.68	1.81	2.08

4.4 *Route lengths in particular tariff zones and outside them for corridor opening towards east*

In order to determine statistical lengths of the voyage routes through particular sections of the route and tariff zones, course of these routes was examined as if ship was proceeding just behind front of ice-free zone during opening of transit corridor through the NSR. Variability of length of ship's routes defined in this way by the NSR is intended to illustrate impact of variability of ice conditions occurring in the subsequent navigation seasons on length of the routes, and thus uncertainty ranges. Statistical results are summarized in Table 2. Lengths of the particular route segments were very similar except tariff zones number 1, 6 and 7. Summed lengths of the route segments up based on average value and median value were very similar.

Table 2. Statistical route lengths and their standard deviation. Compiled by the author based on ice maps of Marginal Ice Zone in ESRI Shape format [13]. Provided courtesy of the U.S . National Ice Center.

Tariff zone	OUT 1 West	1	2	3	4	5	6	7	OUT 2 East	Averaged length of tariff zone	Length of the whole route
Average length [NM}	744	204	466	295	267	391	461	381	161	352.3	3371
St. dev. [nm]	4.9	95.6	125.3	41.6	37.2	40.9	109.1	142.2	1.3	84.6	66.5
Median length [nm]	741.1	162.1	441.7	288.7	262.4	398.9	431.5	340.3	161.0	340.3	3328

4.5 *Ship's operating costs*

Cost of IFO 380 fuel in Rotterdam as of 1st September 2020 of USD 275.5 per metric ton based on current prices given by Ship&Bunker [27]. Cost of chartering PANAMAX-type ships assumed to be USD 14,250 for waters in the Atlantic Ocean outside the Arctic on the basis of the current prices given by Hellenic Shipping News [7]. For delivery of ship in waters of the Arctic Ocean, it was increased by a factor of 2.0 based on separate studies [19]. Therefore, cost of charter in Arctic waters assumed to be USD 28,500 per day and pro rata for use of ship in the NSR region.

5 DISCUSSION OF RESULTS

On basis of formulas presented in chapter 2 and 3.1 as well as average values and standard deviations of input data presented in chapter 3, values of navigational, ecological and economic results of the PANAMAX type ship's voyage in period from 215 to 300 Julian days of the year were calculated (Figures 5-10). It was assumed that this is a maximal time window in which it is possible to consider transit navigation of ships with steel hulls without ice reinforcements on the NSR. Average values (black lines) were enlarged and reduced by one standard deviation ± 1M representing probability of 68.3% and by two standard deviations ± 2M representing probability of 95% (Figures 5, 6, 7, 9 and 10). Value of 95% probability meets the IMO maritime navigation recommendations.

Total average time of transit voyage depends on severity of ice conditions existing during whole voyage. This severity is represented by number of traffic zones where icebreakers assistance is required. The highest severity (number of tariff zones requiring assistance of icebreakers) is at the beginning and at the end of the navigation season, and reduces till null at the mean day of ice-free transit corridor opened on the NSR.

Standard deviation of the total time of voyage changes during the navigation season and ranges from 18.2% at the beginning and end of the season to 24.7% of average value during ice-free window (for 68.3% probability). For a probability of 95% (2M) deviation values of total time of voyage are twice as high, from 36.4% at the beginning and end of the season to 49.4% of average value during ice-free window (Figure 5). Reason of it is greater standard deviation of ship's speed during independent navigation and increasing share of independent navigation from the beginning and end of the navigation season towards average day of ice-free navigation period. Navigation with icebreakers assistance ensures a much smaller standard deviation of total voyage time and thus more precise scheduling of ship's voyage timetable through the NSR.

Total average fuel consumption depends on severity of ice conditions existing during the whole voyage. The highest average fuel consumption is at the beginning and at the end of navigation season, and decreases till minimal at the mean day of ice-free transit corridor opened on the NSR. This is due to higher daily fuel consumption during more severe ice conditions (icebreakers assistance) and lower fuel consumption during lighter ice conditions (independent voyage).

Standard deviation of total average fuel consumption ranges from 19.6% of average value on the beginning and end of the navigation season up to 25.5% during ice-free window (for 68.3% probability). Deviation values for probability of 95% (2M) are twice as high, from 39.2% of average value at the beginning and end of the navigation season to 51.0% during ice-free window (Figure 6). Navigation with icebreakers assistance is associated with a higher standard deviation of fuel consumption and thus less precise determination of deviations in voyage costs at the beginning and at the end of the navigation season.

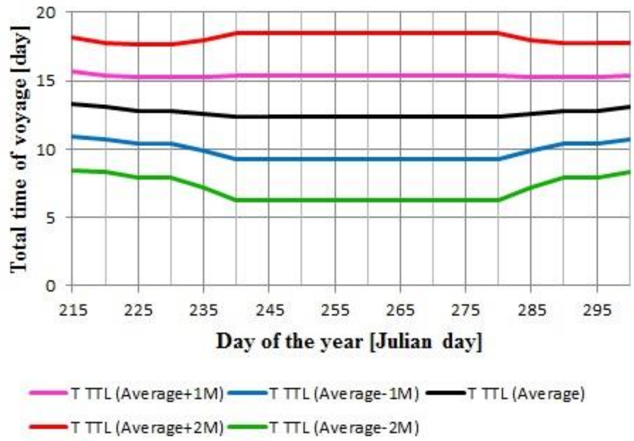

Figure 5. Total average time of transit voyage and voyage time estimation error.

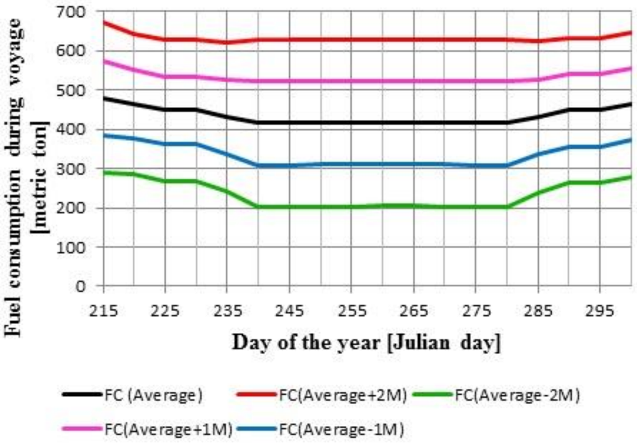

Figure 6. Total average fuel consumption during transit voyage and fuel consumption estimation error.

Changes of total average cost of ship's transit voyage depend mostly on number of the tariff zones where assistance of icebreakers is required due to severity of ice conditions (Figure 7). Costs of fuel consumed and time of voyage (charter of ship) are increasing from external days of summer navigation season towards mean day o ice-free transit corridor but are relatively flat in relation to costs of assistance of icebreakers (Figure 8). Changes of charter cost are around 0.9-3.0% of total costs, changes of fuel consumption costs are around 0.6 – 2.0% of total costs. But changes of cost of required assistance of icebreakers are much higher and are around 32.9 – 42.3% of total costs. To maintain relative stable total costs of voyage it is recommended absolute avoidance of voyage during period of time when severity of ice conditions require assistance of icebreakers.

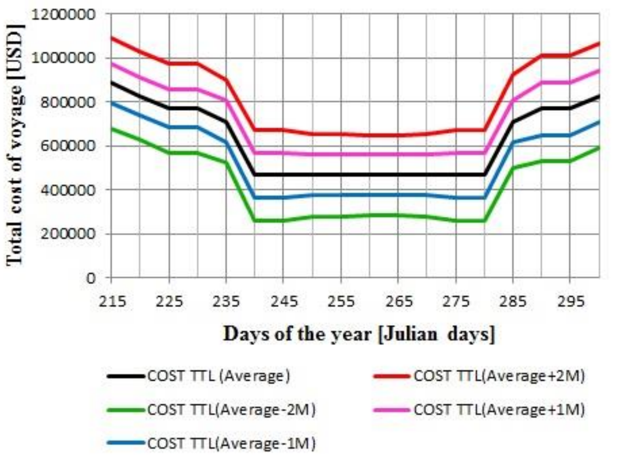

Figure 7. Total average cost of ship's transit voyage and total cost estimation error.

Figure 8. Total average cost of ship's transit voyage and its components.

In the next step, the average fuel consumption per day was calculated for the whole transit voyage for each day the ship was to pass the chocking zone. They were obtained by dividing total fuel consumption by number of voyage days (Figure 9). Values of average fuel consumption increased and reduced by one standard deviation (1M) and two standard deviations (2M) were included on the diagram. The lowest fuel consumption is related to ice-free transit corridor existing along the whole NSR. Fuel consumption increasing with severity of ice conditions towards the beginning and end of the summer navigation season. This is due to daily fuel consumption increasing with the worsening of ice conditions represented by number of tariff zones required assistance of icebreakers (Table 1). Particular lines for fuel consumption with theirs standard deviations are sensitive for standard deviation of daily fuel consumption that is smallest at the mean day of opened ice-free transit corridor and the highest at the beginning and at the end of navigation season (number of tariff zones where was required assistance of icebreakers).

Average fuel consumption per nautical mile passed was calculated for the whole transit voyage for each day the ship was to pass the chocking zone. They were obtained by dividing the total fuel consumption by the average length of the route for the years 2008 – 2020 (Figure 10). Values of average fuel consumption per nautical mile increased and reduced by one standard deviation (1M) and two standard deviations (2M) were included on the diagram. The lowest fuel consumption is related also to ice-free transit corridor existing along the whole NSR. Fuel consumption per nautical mile increasing with severity of ice conditions towards the beginning and end of the summer navigation season. This severity is represented by quantity of tariff zones where assistance of icebreakers was required.

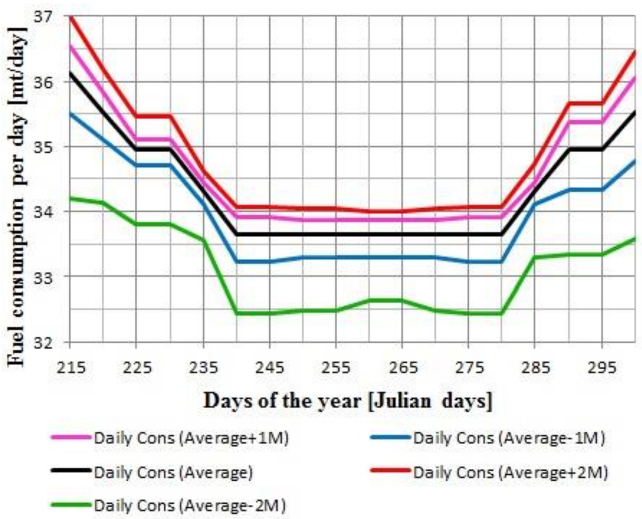

Figure 9. Average fuel consumption per day and estimation error.

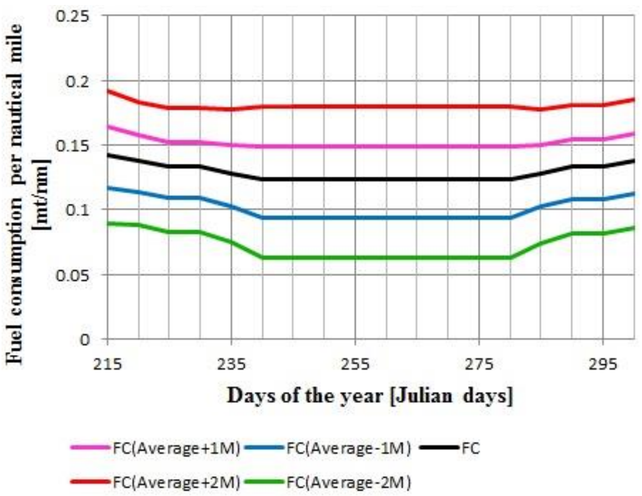

Figure 10. Average fuel consumption per nautical mile passed and estimation error.

Following formula for the expected number of tariffs to be paid for required icebreakers assistance (Equation 13) and formula for standard deviation of these expected number of tariffs (Equation 14) found probable considerable increase or reduce of number of tariff zones (severity of ice conditions) as far as time span from mean day of opened ice-free transit corridor (Figure 11). As negative number of tariff zones requiring assistance of icebreakers is impossible, the limit border for minimal number of that tariff zones should be applied. It is for number of zones requiring assistance of icebreaker k equal null (presented with violet dash line). Following this observation recalculations were performed for formulas 2, 4 and 7. As a result, total average time of voyage, total average fuel consumption, total average costs of voyage, average cost of ship charter, average cost of fuel consumed, average cost of icebreaker assistance, fuel consumption per day and fuel consumption per nautical mile graphs including theirs standard deviations were obtained (Figures 12 – 19).

Lines of average value on graphs that are taking into consideration deviations of number of tariff zones where is required assistance of icebreakers are the same as in the graphs taking into account the standard deviation. However, the lines including probable number of tariff zones k increased or decreased by standard deviation of k with 1M and 2M narrow time window of the lowest values. Average values provide the lowest value time window from 240 to 280 Julian day of the year. Average values of number of tariff zones k increased and decreased by one standard deviation m_k (1M) provide the lowest value time window from 250 to 270 Julian day of the year. Average values k increased and decreased by double standard deviation m_k (2M) provide the lowest value time window from 260 to 265 Julian day of the year. From the above it should be concluded that in order to ensure the lowest navigational, ecological and economic results of the ship's transit voyage through the NSR for average value the ship should pass the chocking zone between 240 and 280 Julian day of the year. For k increased by single standard deviation m_k with probability of 68.5% should pass between 250 and 270 Julian day. For k increased by double standard deviation m_k, ship should pass the chocking zone between 260 and 265 Julian day. The higher the probability of meeting the requirements set by decision-maker when planning a long-term voyage of ship, the shorter time window for meeting these requirements. Outside the favorable time window, the navigational, ecological and economic results of voyage deteriorate very quickly. This is in line with outcomes of Pruyn [22] work.

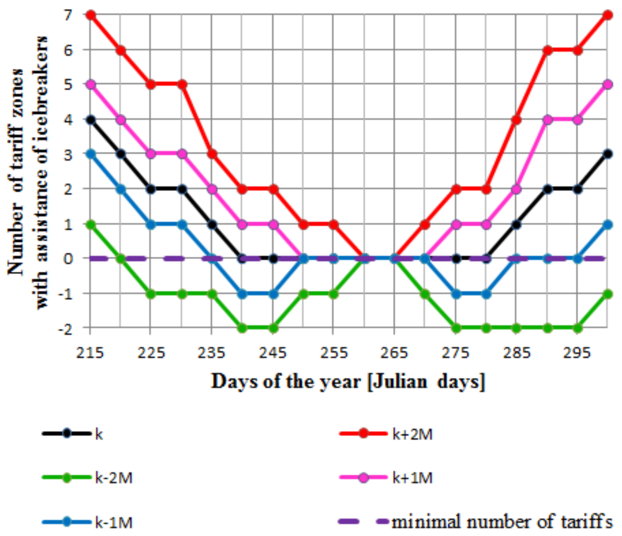

Figure 11. Number of tariff zones k with assistance of icebreakers and its deviation for possible changes

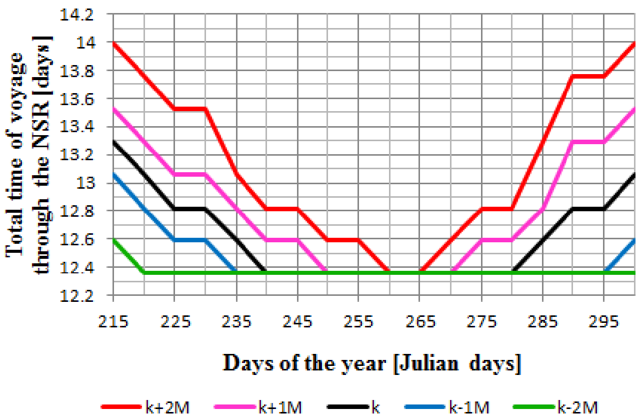

Figure 12. Total average time of voyage and its deviation for possible changes of number of tariff zones required icebreaker assistance.

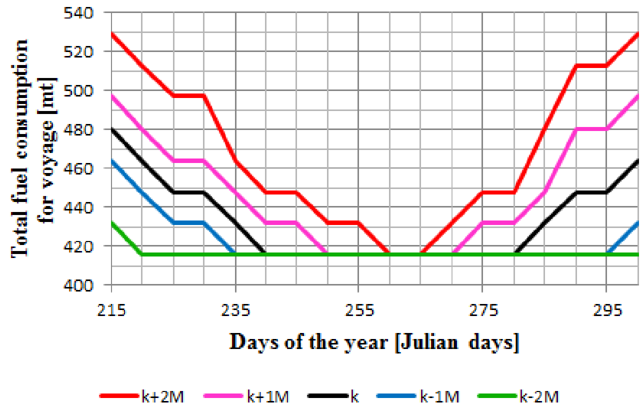

Figure 13. Total average fuel consumption and its deviation for possible changes of number of tariff zones required icebreaker assistance.

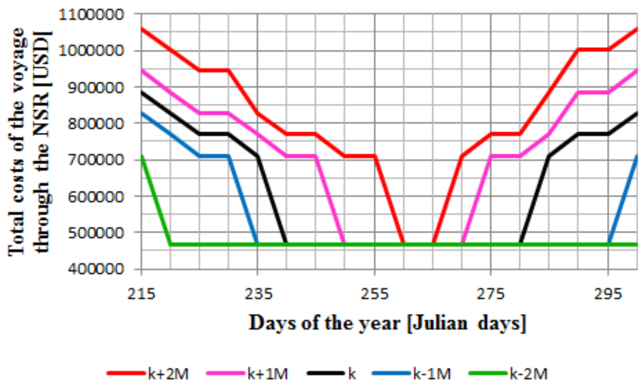

Figure 14. Total average costs of voyage and its deviation for possible changes of number of tariff zones required icebreaker assistance.

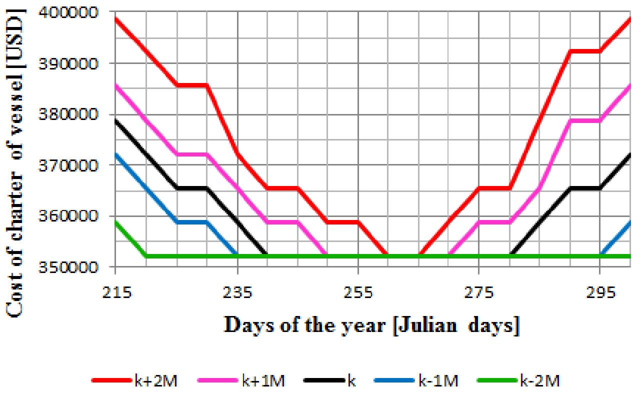

Figure 15. Average cost of ship charter and its deviation for possible changes of number of tariff zones required icebreaker assistance.

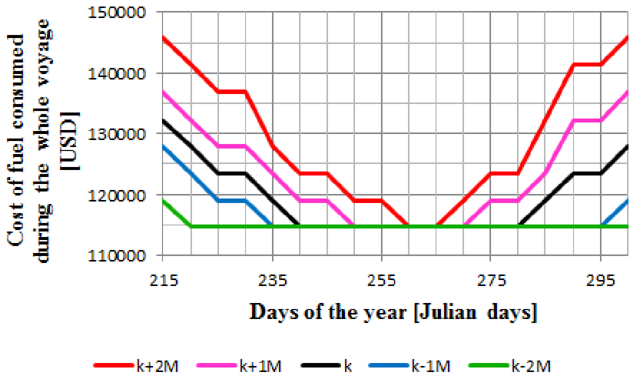

Figure 16. Average cost of fuel consumed during voyage and its deviation for possible changes of number of tariff zones required icebreaker assistance.

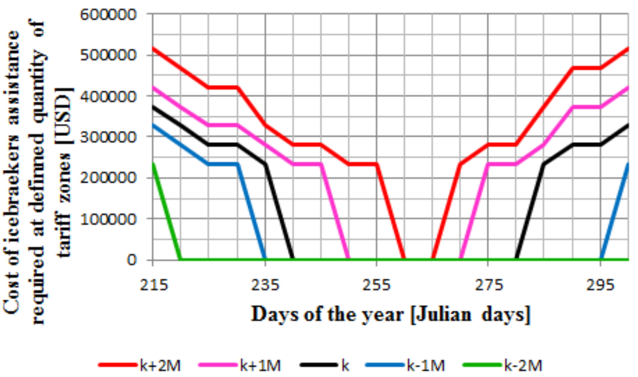

Figure 17. Average cost of icebreaker assistance and its deviation for possible changes of number of tariff zones required icebreaker assistance.

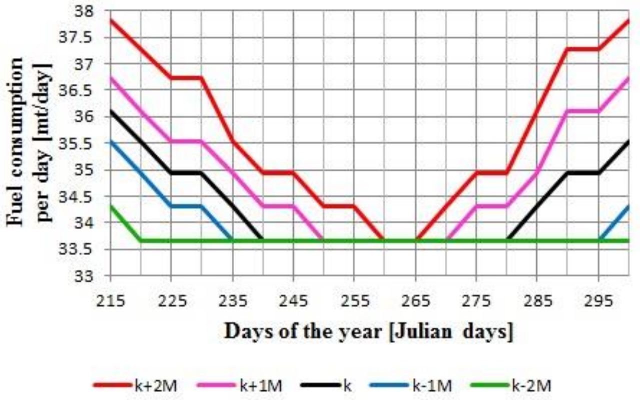

Figure 18. Fuel consumption per day and its deviation for possible changes of number of tariff zones required icebreaker assistance.

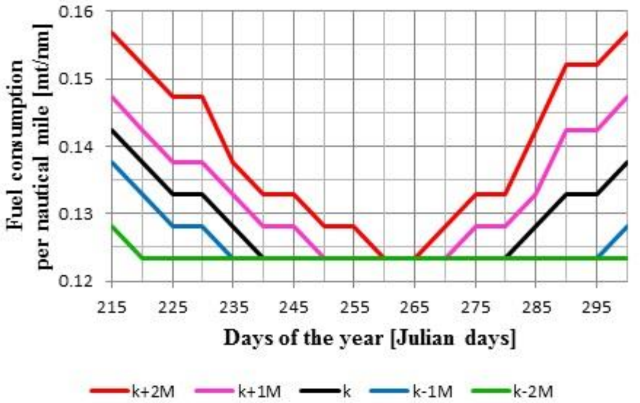

Figure 19. Fuel consumption per nautical mile and its deviation for possible changes of number of tariff zones required icebreaker assistance

6 VERIFICATION OF RESULTS

The formulas presented in the previous chapters were created on the basis of statistical (historical) data for the period of time from 2008 till 2020. These results of the statistical research require verification. Here was decided to use sample of real passage of the ship through the NSR for the year out of the statistical period of time used for creation of the formulas. For creation above mentioned equations the PANAMAX ship was used with the following parameters: DWT=73,140 t, GT 38,489 tons, L=225m, B=32m. In this case decided to use same size ship for verification. Decided to use voyage data also of the bulk carrier Golden Enterprise that made her voyage in early stage of summer season. She departed from Murmansk on 08.08.2021 at 09.8 UTC and guided to Kara Gate. The NSR entered on 10.08.2021 at 2300 UTC and left the NSR at the Bering Strait on 23.08.2021 at 2300 UTC. Her parameters were as follows: DWT 79,471 tons, GT 43,498 tons, L= 229m, B=32m. Her voyage data were available on the interactive map on the CHNL Information Office website [1]. The routes outside the NSR were not exactly same like these used for construction of Equations 1-14. In this case the distances D_{OUT1} and D_{OUT2} from the Equations were used. The corresponding speed was received from averaged speed before entering the NSR and after leaving the NSR. It gave V_{OUT1}= 11.0 knots and V_{OUT2}=12.3 knots. Times of passage through these sections of route were determined with corresponding distances and speeds.

The analyzed ship passed average location of historical ice barrier (chocking zone) on 228 day of the year on 22:55 GMT. According to statistical data (Figures 5-19) it was few days before opening of the NSR for ice-free navigation. Total time of voyage received from formulas was average 13.5 days in the range 10.8 to 16.2 days taking into consideration 1M of standard deviation and from 8.1 to 18.9 days taking into consideration 2M of standard deviation. Recalculated time of voyage duration (taking into consideration the equivalent ports departure and arrival) of analyzed ship in 2021 navigation season was 16.9 days. Result was inside of 2M range, very close to 1M edge. Then prediction of total time of voyage was correct. Number of expected tariff zones requiring assistance of icebreaker assistance received basis formulas was average 2 with possible range from 1 to 3 tariff zones. The analyzed ship in 2021 navigation season encountered 2 ice barriers. One tariff zone at Severnaya Zemlya archipelago and one at East part of Est Siberian Sea. Then prediction of quantity of tariff zones requiring assistance of icebreaker using presented formulas was correct. Following above verification of presented in this work formulas received from historical data assumed are satisfactory for long-term forecasting.

7 SUMMARY AND CONCLUSIONS

Analysis of the resulting graphs leads to several conclusions. The maximal time window in which it is possible to consider transit navigation of ships with steel hulls without ice reinforcements on the NSR is from 215 to 300 Julian days of the year. Total average time of transit voyage and total average fuel consumption are directly proportional to severity of ice conditions encountered during whole voyage. The highest severity (number of tariff zones requiring assistance of icebreakers) is at the beginning and at the end of the navigation season, and reduces till minimal at the mean day of ice-free transit corridor opened on the NSR. A higher standard deviation of fuel consumption during navigation with icebreakers assistance makes less precise determination of voyage costs at the beginning and at the end of navigation season. Total average cost of ship's transit voyage depends mostly on number of tariff zones where assistance of icebreakers is required due to severity of ice conditions. Costs of fuel consumed and time of voyage are increasing from external days of summer navigation season towards mean day o ice-free transit corridor but are relatively flat in relation to costs of assistance of icebreakers. There is recommended avoidance of voyage when severity of ice conditions require assistance of icebreakers in order to maintain relatively low and stable total costs of voyage. Average fuel consumption per day and average fuel consumption per nautical mile are directly proportional to severity of ice conditions. The lowest fuel consumptions are related to ice-free transit corridor existing along the whole NSR. The fuel consumption of icebreaker, when its assistance was required was not taken into consideration.

A ship should pass the chocking zone on the NSR in between 240 and 280 Julian day of the year to ensure the lowest navigational, ecological and economic costs of transit voyage for average value of expected number of tariff zones to be paid for required icebreakers assistance. A ship should pass the chocking zone between 250 and 270 Julian day or between 260 and 265 Julian day to include single standard deviation (68.5%) or double standard deviation (95.0%) of expected number of tariff zones with assistance of icebreakers respectively. The higher probability of meeting requirements set by decision-maker when planning a long-term voyage of a ship, the shorter time window for meeting these requirements. Outside the favorable time window, the navigational, ecological and economic results of voyage deteriorate very quickly and it is in line with outcomes of Pruyn [22] work. Verification of presented in this work formulas received from historical data found consistent with real ship voyage data on early stage of summer navigation season in 2021 year and assumed are satisfactory for long-term forecasting.

The presented statistical method of calculating the results of navigation, ecological and economic voyages of ship that is taking into consideration ice conditions on the basis of historical input data allows forecasting the results of planned long-term transit voyage of the ship through the regions of ice occurrence (3 months in advance and more) on the Northern Sea Route. The method can be applied to other areas where ice is present and in areas where there is no ice. It is then required to use appropriate historical data and develop new input data. The use of formulas for average values of voyage results and theirs standard deviations significantly simplifies construction of the decision model and thus facilitates long-term decision making in case of presence of many input data. Planning information containing average values and standard deviations, and thus average values increased and decreased by single and double standard deviation meet the requirements of the International Maritime Organization. Above all, it facilitate the understanding of the uncertainty ranges. Standard deviations for possible changes of the number of tariff zones where is required icebreaker assistance that are included in the diagrams indicate the time window when the best navigational, ecological and economical results of the ship transit voyage should be obtained. Therefore, the method described in this work can be used in decision support systems.

ACRONYMS

C_{FA} – daily fuel consumption where Full Ahead speed is applied [metric tons/day],
C_{IND} – daily fuel consumption where independent voyage speed is applied [metric tons/day],
C_{IB} – daily fuel consumption where icebreaker assistance speed is applied [metric tons/day],
C_{T} – cost of required assistance of icebreakers related to Gross Tonnage of the ship in between 40,000 and 100,000 GRT [RUB] for tariff zones 1-6,
C_{TTL} – total cost of the voyage [USD],
D_{IB} – mean length of the route segments on the tariff zones for the time period 2008-2020 [nm]; DIB = DIND,
D_{IND} – mean length of the route segments on the tariff zones for the time period 2008-2020 [nm]; DIND = DIB,

D_{IND1} – mean distance from the edge of first tariff zone at the west side of the NSR to the mean location of the chocking zone [nm],
D_{OUT} – mean length of the route segments on the tariff zones for the time period 2008-2020 [nm]; DIB = DIND,
D_{OUT1} – mean length of the route segments from the departure port to the edge of the first tariff zone at the west side of the NSR for the time period 2008-2020 [nm],
D_{OUT2} – mean length of the route segments from the edge of the last tariff zone at the east side of the
FC – fuel consumption for the whole voyage [metric tons],
GT – Gross Register Tonnage of the ship (const.)[register tons],
k – expected number of tariffs to be paid for required icebreakers assistance (rounded down to positive integer) during transit voyage of the ship through the NSR,
$m_k = k'$ – standard deviation of expected number of tariffs to be paid for required icebreakers assistance,
$m_{TTTL} = T'TTL$ – mean error of total time of the voyage [day],
m_{VIB} – standard deviation of speed of the ship on the NSR where assistance of icebreakers is required [kn],
m_{VIND} – standard deviation of speed of the ship on the NSR where areas covered by ice are expected [kn],
m_{VIND1} – standard deviation of speed of the ship from the edge of the first tariff zone at the west side of the NSR till the mean location of the chocking zone [kn],
m_{VFA} – standard deviation of sea speed of the ship (Full Ahead) outside of the NSR [kn],
n – maximal number of the tariff zones on the NSR (n=7),
R – rate of exchange USD to RUB (const.),
T_0 – time of beginning of the ship's voyage at the port of departure [Julian day],
T_{CZ} – time of arrival ship at the chocking zone on the NSR [Julian days of the year].,
m_{TCZ} – standard deviation of time related to defined number of tariffs to be paid (required icebreakers assistance) [Julian days of the year],
T_{END} – time of arrival of the ship's at the port of destination [Julian day],
T_{TTL} – total time of the voyage [day],
T'_0 – standard deviation of the time of beginning of the ship voyage at the port of departure [Julian day],
T'_{END} – mean error of expected time of end of the voyage [Julian day],
m_{DOUT1} – standard deviation of the mean length of the route segments from departure port to the edge of the first tariff zone at the west side of the NSR for the time period 2008-2020 [nm],
V_{FA} – sea speed of the ship (Full Ahead) outside of the NSR [kn],
V_{IB} – speed of the ship on the NSR where assistance of icebreakers is required [kn],
V_{IND} – speed of the ship on the NSR where areas covered by ice are expected [kn].

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