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Simulation Modeling of Marine Transport Systems Operating in Ice Conditions

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ABSTRACT

Evaluation and optimization of the parameters of marine transport systems, which operate in polar regions, is an important research field nowadays. Especially it's important in case of oil and gas transportation. Current practice shows that configuration of the transport system (the number and characteristics of gas carriers or oil tankers, capacity of shore storage etc.) should be determined in the early stages of field development.

Simulation modeling of marine transport systems is an effective method to optimize configuration and characteristics of the transport system in the early stages of field development. This paper is devoted to simulation of marine transport systems, including examples of modeling of LNG transportation from the field in the Barents Sea at various distances using specially developed simulation model. Particular attention is paid to the influence of ice conditions severity on different economic indicators. The article also contains a comparison between traditionally used mathematical programming methods and simulation modeling approach in the context of unstable ice conditions and requirement of regular shipment.

KEY WORDS: Simulation modeling, optimization, marine transportation, arctic

NOMENCLATURE

LNG — Liquified Natural Gas;
MTS — Marine Transport System;
MP – Mathematical programming;
SM – Simulation modeling.

INTRODUCTION

Transport systems associated with the marine transportation of hydrocarbons fulfil an important function in the modern economy and will play the same role in the future. At the same time, global oil and gas projects inevitably shifts to the north, in the shelf zone of the Arctic Ocean. Resources of the largest Russian fields, such as Shtokman, Rusanovskoye, Prirazlomnoye, Dolginskoye and others, are expected about 10 billion tons of oil equivalents (o.e.). The largest field in arctic offshore is Shtokman field, and it is expected about 3.9 trillion cub.m. of gas and 56 million tons of gas condensate. Despite that difficult climatic conditions and technological and economic problems put off start of the Arctic field development, their economic potential is very important.

Arctic offshore development includes an investigation of many important particular issues, and one of them is a marine transportation in ice conditions. One of the most important challenges in this field is an optimization of marine transport system (MTS) configuration (i.e. the number and characteristics of gas carriers or oil tankers, capacity of shore storage etc.) that ensures oil and gas deliveries strictly in time schedule with the smallest transportation expenses.

Arctic transport vessels are usually built for certain MTS and corresponding errors in evaluation of their characteristics can revert back in the future. This is due to the fact that the freight market of ice class tankers and gas carriers practically does not exist, so faults in estimation of quantity and tonnage of such vessels could not be covered by freight market. Furthermore ice class ships lose out in propulsion efficiency and fuel consumption to usual ships and thus they have no possibility to work effectively at freight market. Therefore, the configuration and characteristics of the marine transport system, operating in Arctic conditions, require especially careful investigation and optimization.

Such optimization of marine transport systems is a long-studied problem and there are two basic approaches most often used to solve optimization problems:

- Mathematical programming,
- Simulation modeling.

MATHEMATICAL PROGRAMMING

Mathematical programming (MP) is discipline that concerns the optimum allocation of limited resources among competing activities, under a set of constraints imposed by the nature of the problem being studied. These constraints could reflect economic, technological, marketing, organizational and many other considerations. In broad terms, MP can be defined as a mathematical presentation aimed at finding the best possible allocation of scarce resources.

Formulation of the optimization problem in MP.

General form of an optimization problem in mathematical programming is as follows:

$$f(x_1,....x_n) \to extr$$
$$g_s(x_1,....x_n) \le b_s, \quad s = 1,....m \quad (1)$$
$$x_{i\,\min} \le x_i \le x_{i\,\max}, \quad i = 1,....n$$

where $x_1,....x_n$ - optimized parameters,

$f(x_1,....x_n)$ - objective function (criterion),

$g_s(x_1,....x_n)$ - restrictions imposed on the function of the optimized parameters (restrictions of a function),

b_s – in general, can also be a function of parameters $x_1,....x_n$

$x_{i\,\min}$, $x_{i\,\max}$ - restrictions imposed directly on optimized parameters (explicit restrictions).

All functions in (1) can be nonlinear relatively to its parameters and even statistically distributed. Formulation (1) can be written as follows: find the extremum of objective function (criterion) when all restrictions are considered.

During the 1970-80's MP-approach has been used to develop models of ship traffic in MTS (Pashin, 1983; Sokolov, 1987 and many others), which allows optimizing such parameters as fleet tonnage, vessels speed, schedule of vessels putting into operation etc. under economic criterion. MP-models are analytical and all developed models of MTS have one unique feature: there is only one parameter of vessel's movement in MTS-model that affects the results of MTS optimization. This parameter is the vessel's year transportation capacity at the certain sea road (i.e. ratio of total vessel's year transferred tonnage and year time period), which summaries all vessel particulars, propulsion performance and wind-wave conditions of given sea road. In other words, implementation of this parameter allows defining mathematical programming problem. But, from the other side, implementation of only one parameter of vessel movement leads to non-conformity of the defined model and reality. Furthermore, in general it could be said that MP-approach in case of MTS optimization has got two global drawbacks:

- Timeline does not exist in such a model,
- Implementation of ship navigation logic and vessels interaction is impossible.

Elaborating these two drawbacks it could be said that MP-model is unable to consider the following factors:

1. Time-dependent factors. For example, fouling influence over to fuel consumption, filling level of shore storage, field yield capacity change etc.
2. Regular deliveries of cargoes in case of occurrence of unexpected delays at sea routes (mainly, due to ice conditions). Depending of current situation vessel could increase or decrease her speed in an effort to maintain schedule and this affects fuel consumption.
3. Interaction of icebreacker and cargo vessel during icebreaking assistance. For example, vessel and icebreacker could stand about near ice-edge waiting for each other; forming of vessels' caravan is also a typical method of icebreacking escorting.

These drawbacks partially eliminated in case of traditional MTSs operating in open water conditions, because of negligible influence of wind and waves on difference in steaming time from voyage to voyage and absence of necessity in modeling of vessels' interaction. In case of arctic MTS investigation the following assumptions should be accepted (Zimin, 1985) to provide applicability of MP-approach for this task:

1. Steaming time and fuel consumption are constant, i.e. pre-calculated for each type of the vessel and for each type of ice conditions severity.
2. Icebreaking assistance is unlimited, i.e. escorting vessel by icebreaker at each route segment carried on without any delays.
3. Regularity of deliveries not considered.

As can be seen, MP-approach is bad applicable for MTSs in ice conditions, because schedule is not considered, as well as fuel consumption changes in case if vessel "is in hurry" or "take it slow", also - limited number of icebreakers and so on.

Therefore modern model of arctic MTSs should be based on simulation modeling technique, which allows considering timeline and ship interaction logic. In addition such approach allows not only optimizing of cargo vessels fleet, but also determining required number and particulars of icebreakers, which are very important part of arctic MTS.

SIMULATION MODELING

Simulation modeling (SM) is an effective method to optimize the MTS configuration. SM has an extremely broad scope of application areas each of them has its own modeling techniques. Currently, SM-methods are used more often then MP-methods. This is due to the growth of productivity and the relative cheapness of computing systems, even in comparison with the end of the 1990s.

In the field of transport and logistics problems simulation models are widely used when there is a relatively large number of objects, characterized by simple logic of their movements and simple behaviors.

There are logistic problems which could be described only by means of simulation modeling. For example, a study of the major transportation hubs (ports, terminals), the establishment of land supply chains and storage of cargos (network models of retailers), transportation tasks in production, problems of multimodal transport (mainly containers shipping) and so on.

Currently, there are four main concepts that are used as a framework for the construction of simulation models:

- dynamical systems;
- system dynamics;
- discrete event simulation;
- agent-based models

The first three paradigms were formed in the 2nd half of the XX century, except the agent-based modeling which began to take off in 2000's together with object oriented programming. For several decades, first three concepts, in fact, has not changed, so they are often referred to as traditional.

It should be said that mentioned concepts differs in the complexity of their implementation: agent based approach is the most complex and demands developing of agent behavioral model, applying of GIS[1]-based environment for agents, and has the highest computational complexity. But only agent-based approach allows simulating vessels interaction and thus permits to overcome all drawbacks of MP-approach. Working on agent-based simulation model of arctic MTS is now going on in Krylov Shipbuilding Research Institute (Russia), but description of such a work goes beyond the boundaries of this article and the main attention in this paper is paid to simpler discrete-event MTS modeling. More exactly, discrete-event simulation scenario with regular deliveries of LNG in ice conditions is considered in the paper.

A Discrete-Event Simulation

An idea of system modeling using discrete events was formulated in 1961 by Geoffrey Gordon and implemented in the simulation framework GPSS (General Purpose Simulation System). The first version of the GPSS language was introduced by IBM in October 1961, and with some modifications GPSS is still used for studying simulation modeling.

GPSS language introduced in the modeling paradigm of streaming and network modeling. According to this paradigm, the flow of entities (transactions) moves through a flow diagram that represents logic of the real system. Transactions are waiting in queues, are competing for resources, exercising their processes (services), and eventually leave the system.

[1] GIS – Geographic Information System, which allows geographical reference (gridding) of agents' movement.

A DISCRETE-EVENT SIMULATION MODEL OF MTS

Considered example of the discrete-event model describes scenario of regular LNG export from the shore storage on the Barents Sea shore (Russia) in two directions (i.e. by two sea lines).

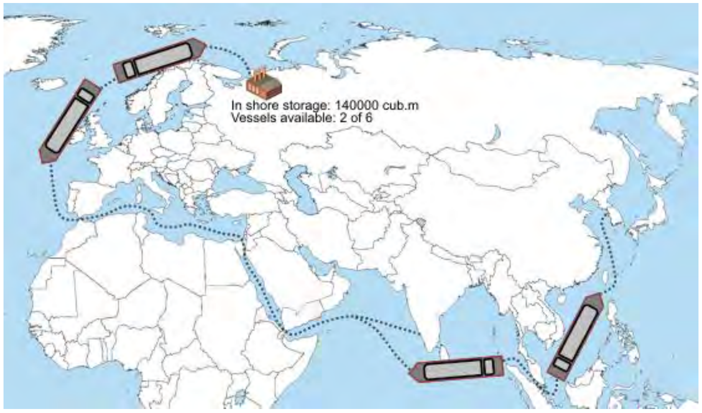

Fig. 1 Layout of considered MTS

LNG export terminal is situated in ice-infested waters. Length of route segments in ice-infested waters represented by the monthly-depend table function for light, medium and heavy ice conditions (Fig. 2).

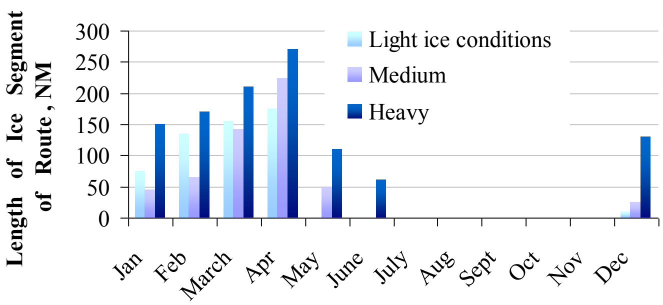

Fig. 2 Length of ice segment of all sea roads

Considered type of LNG carriers – is the membrane type (No96) vessels with a capacity within the range of 40 000 – 260 000 (98%). Ice category of the vessels is ICE1-ICE3 and ARC4-ARC7 according to Russian Maritime Register Rules (RMRS), type of propulsive machinery – dual fuel diesel electric (DFDE), two shafts. Estimation of LNG carriers particulars made by regression-analytical model (Appolonov, 2013) which provides smooth variation of LNG carrier parameters' values (see table 1).

Table 1 Particulars of ARC5 ice class membrane LNG carriers

Capacity (98%), cub.m.	100K	140K	175K	233K
Ice category (RMRS)	ARC5			
Lengh max, m	254.0	286.0	310.0	343.0
Length pp, м	242.8	274.0	296.8	329.1
Breadth, m	38.3	43.0	46.7	51.8
Depth, m	23.9	25.2	25.9	26.8
Design speed, kn	18.87	19.41	19.50	19.50
Icebreaking capability,	0.98	1.05	1.08	1.10
Total shaft power, kW	23 360	30 340	35 480	41 340
DFDE power, kW	35 000	45 000	53 000	62 000
Dw summer, t	51 500	71 300	88 650	117 260
Lightship, t	26 200	34 000	40 400	50 200
Range, NM	12 000			
GRT	68 290	93 310	115 630	153 910
Capacity (98%), cub.m.	100K	140K	175K	233K
Ice category (RMRS)	ARC5			
NRT	20 020	28 040	35 600	49 310
HFO, m3	3 800	4 800	5 600	6 500
Laden condition				
Displacement, t	77 700	105	129 050	167 460
Draft, m	10.9	11.6	12.0	12.6
Cb	0.748	0.752	0.757	0.761
Ballast condition				
Displacement, t	64 500	85 500	102 900	130 200
Draft, m	9.3	9.6	9.8	10.1
Cb	0.731	0.732	0.736	0.738

It should be noted that all details of considered MTS (number of lines, ice conditions etc) are taken for example and developed simulation model could treat other initial data.

Model Description

Described simulation model designed using AnyLogic simulation software, which allows animating the model and observing the details of its running.

According discrete-event simulation approach, LNG cargo volumes posed as an "entities", while LNG carriers perform "resources" functions.

Model takes the following input data:

- The annual LNG flow - general cargo traffic generated at the LNG plant, which have to be transported in two directions in a single year. Set directly.
- Lines distances - total distance for both lines. Set directly.
- Ice section length - depending on the severity of ice conditions and season. Set by table function
- Lines demand - determines the relative demand for both lines on the current flow of LNG (100% in total). Set directly.
- The quantity of gas carriers - the total number of gas carriers, which will be used in the simulated transport system. Set directly.
- Capacity of gas carriers - payload of gas carriers, that is the same for all vessels. Set directly.
- Ice class of gas carriers. Set directly.
- The maximum capacity of the shore storage - an optional parameter that limits the maximum allowable shore storage capacity. If not specified, shore storage capacity has conditionally unlimited amount. The actual capacity of shore storage is determined by the model run.

The flow chart shown in Fig. 3 displays the main components of MTS discrete-event model, operating in ice conditions.

Model consists of the following main elements:

1. *entitySource* – creates entity under condition that there is the simultaneous presence of ballast vessel at the port and a cargo volume in the shore storage. LNG cargo volume is equal to capacity of the vessel.

2. *resourcePool* – a place, where all available in the transport system LNG carriers appears at the start of modeling (export port of the MTS). After returning from the voyage, the LNG carrier also waits for the entity here.

3. *resourceSeize* – represent a process when an entity seizes resource, i.e. it is a process of LNG loading on gas carrier. It has a certain duration equal to the duration of the loading operation. When "resourceSeize" happen, the LNG cargo volume is removed from shore storage.

4. *selectOutput* – a place where loaded vessels apportion to the lines.

5. *iceDelayLoaded* (1,2) – delay that characterizes time of passing the ice segment of route by loaded vessel. Delay time varies depending the season and stochastic fluctuations caused by uncertainty of severity of

ice conditions.
6. *delayLoaded* (1,2) – delay that determines time of passing all distance except the ice segment to the destination port by loaded vessel. This delay depends on cruising speed of the vessel, or on the predefined delivery schedules. If the vessel is not physically able to deliver LNG cargo volume in time schedule, the current configuration of MTS is recognized as infeasible. This delay may also contain some stochastic fluctuations, but their impact on the system is much weaker than the ice delays due to long length of LNG carriers and relatively small added wind-wave resistance.

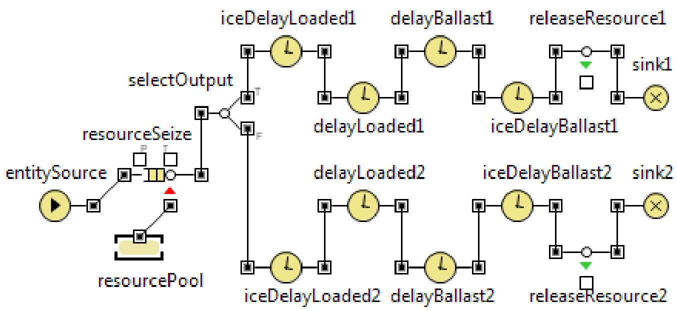

Fig. 3 Components of discrete-event MTS-model

7. *delayBallast* (1,2) – the same as "delayLoaded" but with regard to ballast vessel.
8. *iceDelayBallast* (1,2) – the same as "iceDelayLoaded" but with regard to ballast vessel..
9. *releaseResource*[2] (1,2) – this part frees resources (vessels). After this event, the resource (LNG carrier) is available again in *resourcePool* and can be seized by the application.
10. *sink* (1,2) - destroys entities.
Discrete event modeling is a powerful tool, but implementation of ship navigation logic is impossible to it. To overcome this drawback special approach is applied in this model. All LNG carriers' movement on the open water in ballast condition in the model happens with the highest speeds and highest fuel consumptions. After one LNG carrier round voyage finished, vessel's down time calculator starts and summaries elapsed time until the next round voyage. Calculated in this way time after simulation summarizes with steaming time at maximum speed that result in "actual" steaming time in ballast condition, which allows to reduce primary fuel consumption at highest speed. It should be noted that laden vessel chose a speed rate with regard to delivery time according to schedule. In such a manner complex logic of speed rate choice could be considered. But it is possible with relatively simple models, when ship interaction does not implicate.
Also, as was stated above, during the simulation there may be occurrences when the current set of input parameters is not able (even at the highest vessels' speed) to provide the required LNG transportation amount (annual flow). Such sets of parameters recognized as infeasible.
Except the mentioned basic elements, model contains auxiliary events, variables, functions and state diagrams. Model running is impossible without them; however, a detailed description of these elements is outside the scope of this paper. But one circumstance needs the comments. Designed model aimed the MTS optimization and comparison of different variants of MTS configuration. But correct variant comparison is possible when each variant (i.e. number of vessels and their capacity) evaluated in an optimum schedule (arrival times, apportion to the lines, delays and so on). For each variant schedule changes results in 5-10% fluctuations of the economic criterion, therefore in general such tasks might be called schedule-sensitive. So a number of internal schedule variables are implemented in the current model, and when the input parameters are stated in the model, internal algorithm find the best schedule for each variant of MTS configuration. This process permits optimization to be correct.

[2] Terms such as "Sieze" or "Release" are typical for discrete-event simulation and originate from the GPSS modeling language

OPTIMIZATION OF MTS CONFIGURATION
In general, optimization in simulation modeling can be performed in two ways:
1. By means of direct multiple runs of the simulation model and varying the inputs considering the limits. This method is applicable if the number of variable parameters (the number of iterations) is not large. This method is also good because it can save a criterion values on each iteration and then it will offer to observe criterion dynamics in charts.
2. By means of mathematical optimization methods. In this case, the number of iterations significantly reduces, but at the same time mathematical tool for the optimization experiment need to be developed. This method is useful for a large number of variable parameters. However, there is special software that helps to realize this kind of optimization. For example, the optimizer OptQuest is embedded in AnyLogic software.

Optimization criterions & expenses calculation
The designed simulation model allows to optimize the MTS structure by one of ways, proposed above. First of all, it is necessary to introduce optimization criteria such as:

- total expenses (capital and/or operational)
- discounted expenses (capital and/or operation)
- unit transportation cost
- other criteria

Capital vessels building cost depends on several inputs: number of sisterships, LNG capacity, ice class. Capital shore storage building cost is determined after system modeling and depends on real ultimate capacity or predefined shore storage capacity.
Operation expenses counted during the simulation progress. For these purposes the key points of the model (the arrival of vessel in port, cargo operations, etc.) are converted into the current operation costs.
The optimization criterion is most influenced by operational fuel expenses. For realization of the calculation for a single voyage is used a special function that determines the cost of fuel, depending on:

- distance of the voyage,
- elapsed time,
- vessel ice class
- ice segment length an ice properties

After simulation running, the final value of optimization criterion is determined.

Variable parameters
The optimization problem in our case is reduced to determination of the optimal MTS configuration for the specified inputs. The optimization is performed by variation of the following parameters:

- The quantity of LNG carriers,
- Capacity of LNG carriers,
- Ice class of LNG carriers.

And the following could be considered as an input data:

- Annual LNG flow,
- Lines demand,
- Lines distances,
- Parameters of ice coverage (length of ice segment, ice properties).

It is advisable not to vary all parameters at once, but specific combination thereof, fixing the other parameters.
In addition to variable parameters listed above, the required shore storage capacity will be also referred to the transport system

"configuration". Shore storage capacity is not the input parameter, but is determined in result of MTS modeling.

Optimization example

As already mentioned, the optimization can be carried out by means of direct model runs and by using mathematical optimization methods. Here is an example of the experiment, which is implemented using the direct model runs.

Objective: find the minimum value of the criterion "capital and operation expenses for 25 years" for a given annual LNG flow, lines distances and ice conditions severity, by varying the parameters "the quantity of LNG carriers" and "capacity of LNG carriers ". Parameters settings for optimization experiment are shown in tables 2-3.

Table 2 Non-variable parameters settings

Parameter	Value
The annual LNG flow	7000K cub.m.
Line 1 distance	8000 NM
Line 2 distance	12000 NM
Ice conditions	Heavy
Ice class of gas carriers	ARC5
Lines demand	50/50 %

Table 3 Variable parameters setting

Parameter	Minimum value	Maximum value	Step
The quantity of gas carriers, u	6	10	1
Annual number of voyages[3], u	30	62	2

The results of the experiment are shown in Fig. 4.

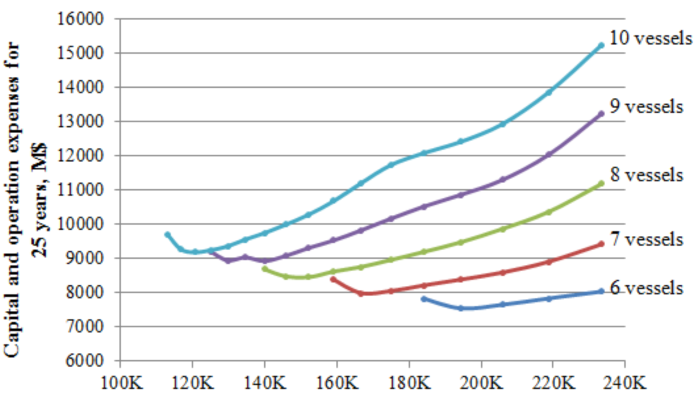

Fig. 4 Results of the optimization experiment

As it could be seen, the minimum value of the criteria corresponds the variant with 6 gas carriers of 194 400 cub.m. capacity.

Non-optimization experiments

Direct model runs with different parameters settings can also be used for the sensitivity analysis of marine transport system. For example, Fig. 5 shows the influence of ice conditions severity and vessels capacity on criterion value. The quantity of vessels is 7.

It could be seen, that 7 vessels with 152 000 cub.m. capacity and less will not cope with specified LNG flow in heavy ice conditions. Also the difference between criterion values in light and medium conditions is much less than this difference in medium and heavy conditions.

[3] This parameter determines capacity (Q) of gas carriers. Q = annual LNG flow / annual number of voyages

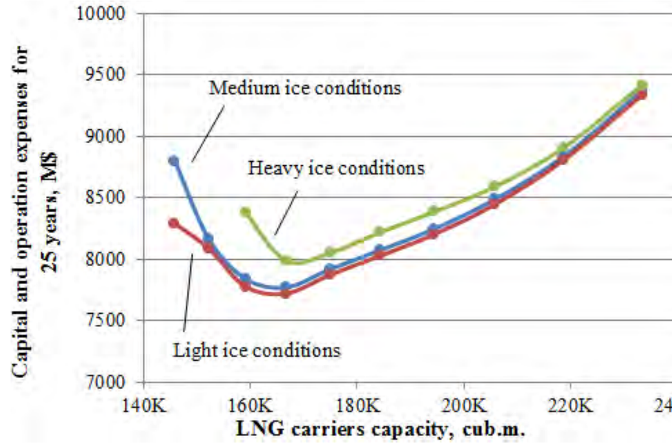

Fig. 5 The results of the experiment

CONCLUSIONS

Modeling of marine transport systems (MTS), operating in ice conditions, is an important problem due to the modern trends in arctic shelf fields' development.

The analysis of existing methods of marine transport system modeling has shown that traditionally used mathematical programming (MP) approach have serious weaknesses:

- Timeline does not exist in mathematical programming model,
- Implementation of ship navigation logic and vessels interaction is impossible.

They restrict application of MP-methods for MTS optimization tasks where time-dependent factors and vessels' interaction should be modeled.

Simulation modeling (SM) could resolve these problems with using of discrete-event or agent-based paradigms. Discrete-event modeling is relatively easy instrument, which could consider only timeline factor. Such type of MTS modeling is a powerful tool that can help to observe how marine transport system works in a timeline. Complex agent-based model allows simulating not only timeline, but also vessels interaction that permits to overcome all drawbacks of MP-approach. Last is the most important for arctic MTS investigation, for which interaction of icebreacker and cargo vessel during icebreaking assistance and logic of ship navigation in ice are a prime of importance. It also could be said MTS simulation modeling is a very promising area to study.

The discrete-event model described in this paper shows that modern simulation modeling software is actually applicable for considered problems and may be used for MTS optimization.

Optimization in SM can be performed by two ways: either by means of direct multiple runs of the simulation model or by means of mathematical optimization methods. It expands opportunities of SM, because direct models runs can also be used for the sensitivity analysis of MTS under action of different factors.

Finally it could be said, that simulation modeling is a nessesary stage of design of any modern MTS, particularly MTS operating in Arctic areas.

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