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MULTIDISCIPLINARY APPROACH TO DESIGN AND ANALYSIS OF ARCTIC MARINE TRANSPORT SYSTEMS

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ABSTRACT

Basic principles of the multidisciplinary approach to arctic marine transport systems (MTS) design and analysis are described in the article. The main idea of the approach is to synthesize geographic information system (GIS) technologies, different shipbuilding disciplines, fleet planning instruments and agent-based dynamic simulation models in an integrated software framework on the basis of object-oriented programming. Vessel operation is described as the movement and interaction of independent ships in GIS environment within the framework of the simulation model. MTS operation combines vessel operation itself (routing, determination of speed and fuel consumption, icebreaker escort, etc.) with plenty of external entities (port infrastructure, ice channel freezing process, offshore platform operation, etc.) that could be described as systems with comprehensive logic and physical behavior. Such integration provides a new quality of MTS simulation that allows considering complex interconnection of various subsystems and all the important details of each MTS project. The outline of the program framework to realize such an approach is given, and two case studies are described to demonstrate its capabilities and feasibility.

Key words: marine transport systems, fleet simulation, marine logistics, ice class ships design, fleet sizing, multidisciplinary approach, ice routing.

1. INTRODUCTION

The development of new offshore projects in the Arctic begins with a comprehensive analysis of MTS performance, which significantly affects the economic indicators of the whole project. According to a number of special studies, the share of MTS in total expenses of Arctic offshore projects increases with the growth of sailing distance and vessel ice class and may reach the value of 30-50% [1]. It means that investigation of MTS efficiency has a great importance for the Arctic offshore industry, especially due to the lack of full-scale experience.

Along with that, MTS investigation is a quite difficult task from a methodological point of view because it requires application of methods and approaches from different subject areas. In the most general case such a task involves a definition of the fleet configuration (fleet sizing) and further analysis of MTS performance considering detailed ship parameters, various cargo types, port characteristics, weather conditions, navigational features, etc. It demands the usage of a wide range of scientific disciplines that have their own theoretical background and methodology. They are:

- simulation of complex systems;
- ship design in general;
- ship propulsion performance in ice and open water;
- definition of fleet configuration (maritime fleet sizing);
- vessel routing, scheduling and operating control;
- metocean and ice conditions modeling;
- weather routing of ships including routing in ice;
- system analysis, algorithmization and programming;
- simulation of navigation processes;
- economic analysis and feasibility study.

At the same time, researchers with different professional orientation (shipbuilders, logisticians, etc.) tend to make their investigations of MTS in very different ways, considering mainly those aspects of MTS that are familiar for them.

A wide range of specialists in shipbuilding are used to consider MTS in the context of ship design [2, 3], concerning primarily design aspects (main particulars, hull form, type of propulsion, etc.). Even if MTS is considered as some external factor, it plays a secondary role, which is necessary to solve ship design task. Some examples could be given here. Studies led by academician V.M. Pashin in the 1970-ies [4] suggest a two-level ship optimization concept where the top level optimization is intended to define such MTS parameters as the number of ships and their main characteristics (dimensions, speed, cargo capacity, hull form coefficients, etc.) by means of mathematical programming (i.e. simplified MTS representation). The lower level is dedicated to ship sub-system design, e.g., sub-system "hull" is described by such optimizable parameters as frame spacing, etc. The main point of [4] is that special "marginal cost" approach is proposed to provide criteria for sub-system optimization in strict accordance with top level optimum criterion. Unfortunately, this most interesting scientific work is available in Russian only. In [5] a ship is considered in a context of five design aspects: structural, behavioral, contextual, temporal and perceptual. The last three ones indirectly involve MTS. In [6] a system based approach is proposed to establish a link between ship, ship sub-systems and MTS. This list could be continued but, due to paper size restrictions, we should stop here and conclude that, from the author's point of view, there is a clear tendency in shipbuilding society to consider MTS in the context of ship design without going deep into operational parameters and logistic aspects. It follows from the tasks that shipbuilders used to solve.

Specialists in ship's ice resistance and arctic voyage time estimation consider MTS mainly from the point of view of vessel movement through ice and time consumption in various ice conditions. A number of related computational models have been developed. Ref. [7] contains the description of an empirical-statistical model that is based on full-scale data approximations for arctic ships. Transit simulation approach is developed in [8]. It assumes calculation of speed of ship transit through modeled ice profile (floe ice, ridges, open water) in "second per second" mode using ice resistance estimations by means of empirical formulae. Machine learning techniques (Bayesian algorithm) based on full-scale observations are used in [9] to predict vessel performance in ice. All these algorithms could be used to solve ice routing problems [10, 11] but the investigation of ice voyage time is obviously not enough to consider MTS in general. For this reason, a number of discrete-event simulation models for arctic MTSs have been developed (see [12, 13]). These models are based on precalculated voyage time data; weather windows at ports are not considered; a great number of factors influencing vessel logistics and operating control are also omitted. Such simulation models are similar to a queue system and suitable either for very simple transport systems or for preliminary calculations.

At the same time, detailed study of related logistic tasks such as fleet sizing and route planning is common for specialists in marine logistics; a thorough description of the state of the art in this area is given in [14, 15]. The peculiarity of a logistic approach is the usage of ship movement models in various ambient conditions that are quite simplified from the point of view of resistance and propulsion. Various aspects of ship design and optimization of main particulars are not considered, i.e. mainly fixed MTS configurations are under investigation. In addition, such parameters as restricted areas and volumes of on-shore storages and cargo flow dynamics are usually treated only in special, simulation-based case studies.

Thus, despite some partial description of these tendencies, a conclusion could be drawn that nowadays there is no practical instrument to investigate arctic MTS itself, considering all necessary aspects at a high level of detail. In case of complicated MTS this may result in inaccurate conclusions in general. Therefore the main aim of this paper is to describe the basic principles of new practical multidisciplinary approach for arctic MTS design and analysis, which allows the integration of shipbuilding, logistic, ice-performance and other related tasks. The approach is realized as an integrated extensible software framework where theoretical background and program architecture provide a possibility to accumulate different calculation algorithms for their simultaneous use in practice. This study started in Krylov State Research Centre in 2012.

2. MULTIDISCIPLINARY APPROACH

The main idea of multidisciplinary approach is to create a framework that integrates methods from various disciplines using the following information technologies:

- Object-oriented approach (OO approach);
- Geo-information systems (GIS);
- Dynamic simulation models.

2.1. OBJECT-ORIENTED APPROACH

Useful opportunities offered by the OO approach in ship design research were highlighted back in the 1990-ies [16] but practical implementation of this approach in research applications is still constrained by the peculiar conservatism of shipbuilders. The paradigm of OO approach perfectly suits the principle of ship representation as a complex engineering system, while MTS is treated as a higher-hierarchy-level system with respect to the ship. Therefore, a wide usage of the object-oriented approach for MTS analysis and design has been a priority in current study. For this purpose, comprehensive efforts were undertaken to perform system analysis, decomposition, and formal description of MTS elements to obtain the object model of the framework. Full description of the latter is beyond the scope of this paper, therefore only the illustration of a small part of the object model is given below. Fig.1 shows the description of the ship and carried cargoes in standard UML notation [17].

The logic class "Ship" has a large number of attributes describing ship parameters which are independent of loading conditions. This class also includes one or more structures ("Groups of propellers", "Loading conditions") that are relevant to propeller parameters and ship particulars dependent on loading conditions (displacement, towing resistance, etc.). The "Ship" may contain an arbitrary number of cargo spaces and cargo handling devices, whose performance is described by a set of items in the "Parameters of cargo handling" class. Cargo spaces are divided into on-board and on-shore spaces (not shown at Fig.1); their general characteristics and behaviour are encapsulated in the abstract class “Cargo space”. Its most important characteristic is “Cargo space description” containing space utilization coefficients for each type of cargo as well as indications of combined placement, which defines whether more than one type of cargo can be contained in this cargo space. Two logic types of cargo are identified: general cargo (cargo units characterized by volume, area and mass) and bulk cargo (characterized by density). According to this classification the bulk cargo also includes liquid cargoes. Vessel description also contains such classes as “Groups of engines” and “Power consumption modes” (not shown at Fig.1) that allows calculating fuel consumption for hotel load, cargo heating, etc. So, the main attributes of a ship treated as an MTS element are the ship’s cargo spaces, loading conditions, propulsion performance and fuel consumption because these elements are essential functional characteristics of the ship as a part of a transport system.

Not only ships but also ports, platforms and floating storages are represented as objects. Each object has its internal structure and is described by the set of static parameters and phase variables that determine its current status. For example, apart from cargo spaces and cargo handling devices the port description includes the description of roadsteads, jetties, internal harbour routes, weather windows and other elements.

In essence it could be said that the OO approach best suits the philosophy of system approach and enables to model complex MTS structures as well as to integrate various subsystems into more sophisticated systems.

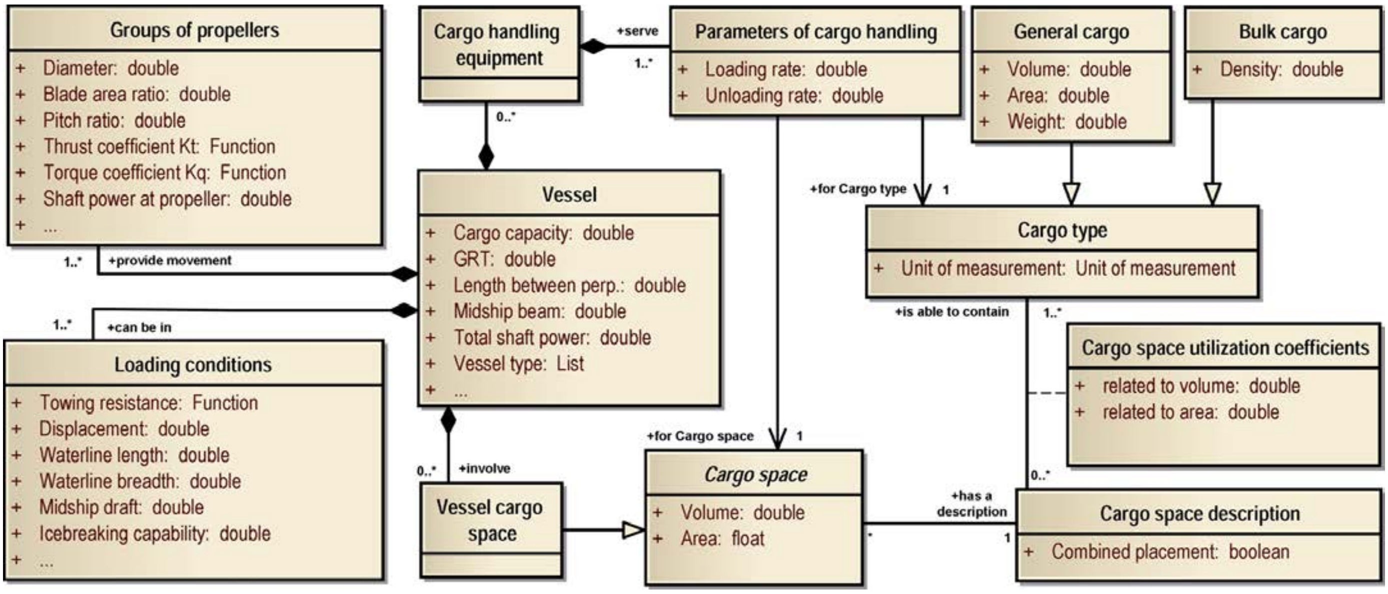

Fig. 1. Class diagram of ship & cargo object model in UML notation (part of general model)

2.2. GEO-INFORMATION SYSTEMS

GIS environment which is used to model ship movement contains four types of data, stored in shape-files, grid-formats or tile-layers. They are:

- layers of navigation geographic space;
- layers and databases of metocean conditions essential to estimate ship sailing parameters;
- areas with special logic or economic constraints;
- mapping information layers.

The geographic space for navigation (see Fig.2) contains: roadsteads, shoreline, water depths (GEBCO and ETOPO data bases), standard pre-defined routes (fairway channels, internal port routes) and a layer of restricted navigation area. The latter layer envelops shallow water areas of less than 20-meter depths, it also smoothens the shoreline contours to simplify ship’s automatic navigation during the simulation process. Ship operation within restricted areas is allowed only by pre-defined routes, while outside these areas ships are allowed to sail freely.

The metocean layers include regions and related databases containing stochastic parameters of winds and waves, visibility, characteristics of ice and ice compressions, etc. Ice data is defined and stored using the grid format. The entire area of Russian Arctic seas is covered with a regular longitude-latitude grid of 0.25 deg. resolution. For each grid cell the ice parameters for light, medium, heavy and extreme ice conditions are defined by months. Ice parameters include ice concentration, age, floe size, ridging (hummocking), snow cover, stage of melting, probability of ice compressions, as well as ice strength characteristics, i.e. all the parameters required to calculate ship speed and fuel consumption in ice. Integral ice severity is shown at Fig.2 by color: the lighter color gradation of grid cell, the more sever ice within it. All ice data was provided by the Arctic Antarctic Research Institute (AARI) based on archive ice charts (1960-2014) [18] in Sigrid-3 format. Many experts dealing with MTS investigation traditionally describe ice environments using a different approach when ice conditions are represented for specific shipping routes (see e.g. [6, 8]). Although this representation provides relatively simple data input and checkup, it obviously constrains layout of port locations and shipping routes. For this reason, an alternative grid-based approach is used to enable analysis of arbitrary MTS layouts. The wind/wave layer (shape-file format) contains wind and wave statistics for all regions of the world ocean. These data are taken into account in calculations of ship navigation characteristics along with sea bathymetry data and visibility conditions.

In practical MTS simulation it is often required to consider specific information with GIS reference. For this purpose, special program technology was developed to define geographical regions with different tax regulations (e.g. port-charges depending on the ship particulars, seasons of the year and cargo characteristics), emission restrictions, season constraints to navigation, etc.

The same type of regions was used to define areas of icebreaker responsibility.

Besides the data, which is directly used for various calculations, an important role in initial data preparation and MTS simulation is played by information support layers. They provide locations and names of cities, straits, fairways, rail roads, etc. At current time, these layers are represented using the tile format and OpenStreetMap web service.

It can be concluded that application of GIS technologies for MTS description and simulation enables not only to reduce time for input data preparation, but mainly provides practical possibility of implementation of ship operation and interaction logic, which are closely connected with geo-information space.

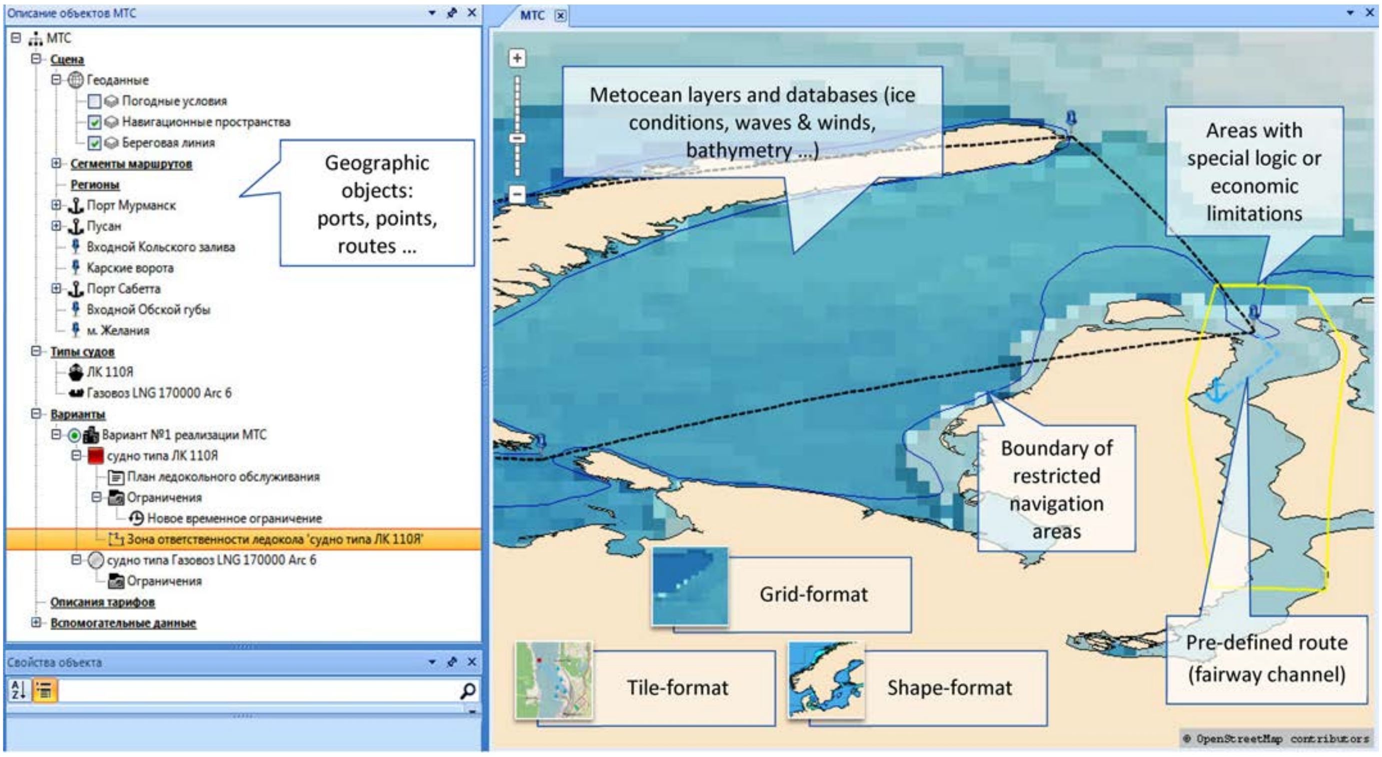

Fig. 2. Main GIS data for MTS simulation

2.3. DYNAMIC SIMULATION MODELS

The following methods, which are listed in order of increasing computational complexity, are traditionally used for MTS analysis and ship design (preferred area of application indicated in brackets) [19]:

- expert analytics (definition of fleet configuration and other MTS parameters using analytic formulae and expert estimations);
- queuing theory (modeling of ship operations in harbours and gateways, operation of offshore service vessels);
- graph theory and combinatorial optimization (vessel routing and scheduling);
- linear and non-linear mathematical programming (optimized fleet configuration to support the required freight traffic for multiple ports);
- discrete-event or agent-based simulation modelling (MTS complex analysis and design).

Most of above-listed methods can be used for comparison and optimisation of fleet configuration at design stage (fleet sizing). But each method has corresponding restrictions due to the ability or inability to consider various factors and schemes of fleet operation. The necessary condition of use of these techniques is a high-speed performance of models, which should be sufficient to carry out numerous comparisons and optimizations. Obviously, such computational models of “design type” should be not too detailed with regard to ship navigation, environmental modelling, time scheduling, etc. On the contrary, in order to obtain more accurate quantitative estimations and a vivid visualization of MTS with fixed configuration (i.e. in the case when the computational speed of the model is not so critical), agent-based simulation modelling is to be used [20]. This technology is able to give an adequate and consistent operational model of MTS with non-linear operating schemes or complex logic relations among elements (ice-going vessels and icebreakers, offshore support ships, auxiliary vessels, etc.). The agent-based model perfectly matches the system approach and OO philosophy and, therefore, it is appropriate to support the multidisciplinary model of MTS providing a broad range of opportunities while having, on the other hand, a rather high computational complexity.

For this reason, in the software solution intended for MTS analysis (see item 3) there are different numerical models dedicated to computation of the fleet configuration and optimization of ship characteristics (i.e. to "design a ship in the context of MTS" according to shipbuilding terminology) and detached agent-based models for detailed investigation of the fixed configurations of MTS. According to authors' experience, the latter task is of more practical interest at present. The point is that customers and ship designers tend to underrate optimization of ships and MTS at design stage, while it is often required to analyse operation of MTS, whose characteristics were chosen based on expert opinion or simple estimations.

The developed agent-based MTS model utilizes the following principle of simulation: ships are represented as individual complex objects (agents) operating and interacting in GIS environment under control of logic (planning) algorithms. The simulation model (see Fig. 3) is realized in the AnyLogic® IDE and simulates ship movement, storage filling dynamics, port weather windows and many other MTS processes according to requirements of each current study. The history of any operating parameter or state variable in the model can be logged and further analysed using standard post-processing routines. Specific parameters having probabilistic nature like maximum storage filling levels are obtained and statistically analysed by means of multiple runs of the simulation model.

Ship movement is modelled in stochastic environment conditions. Its speed and fuel consumption are computed by separate software module "Mechanic" [21]. This module implements the methods for estimation of ship propulsion performance in all types of environmental conditions including: calm water, wind & waves (considering mandatory speed decrease); independent operation in ice conditions (including hull strength constraints); operation under icebreaker assistance and in freezing channel. Restricted water depth, hull fouling (in open water) and hull roughness (in ice) are also taken into account. Functionality of "Mechanic" module allows modelling multi-shaft vessels as well as various types of power plants based on different principles of power transmission to propeller shafts. Ship sailing parameters are computed for any feasible loading cases of propulsion system at any combination of environmental conditions. In other words, the "Mechanic" module is a multi-purpose computational tool encapsulating a range of various existing and original methods for estimation of ship propulsion performance.

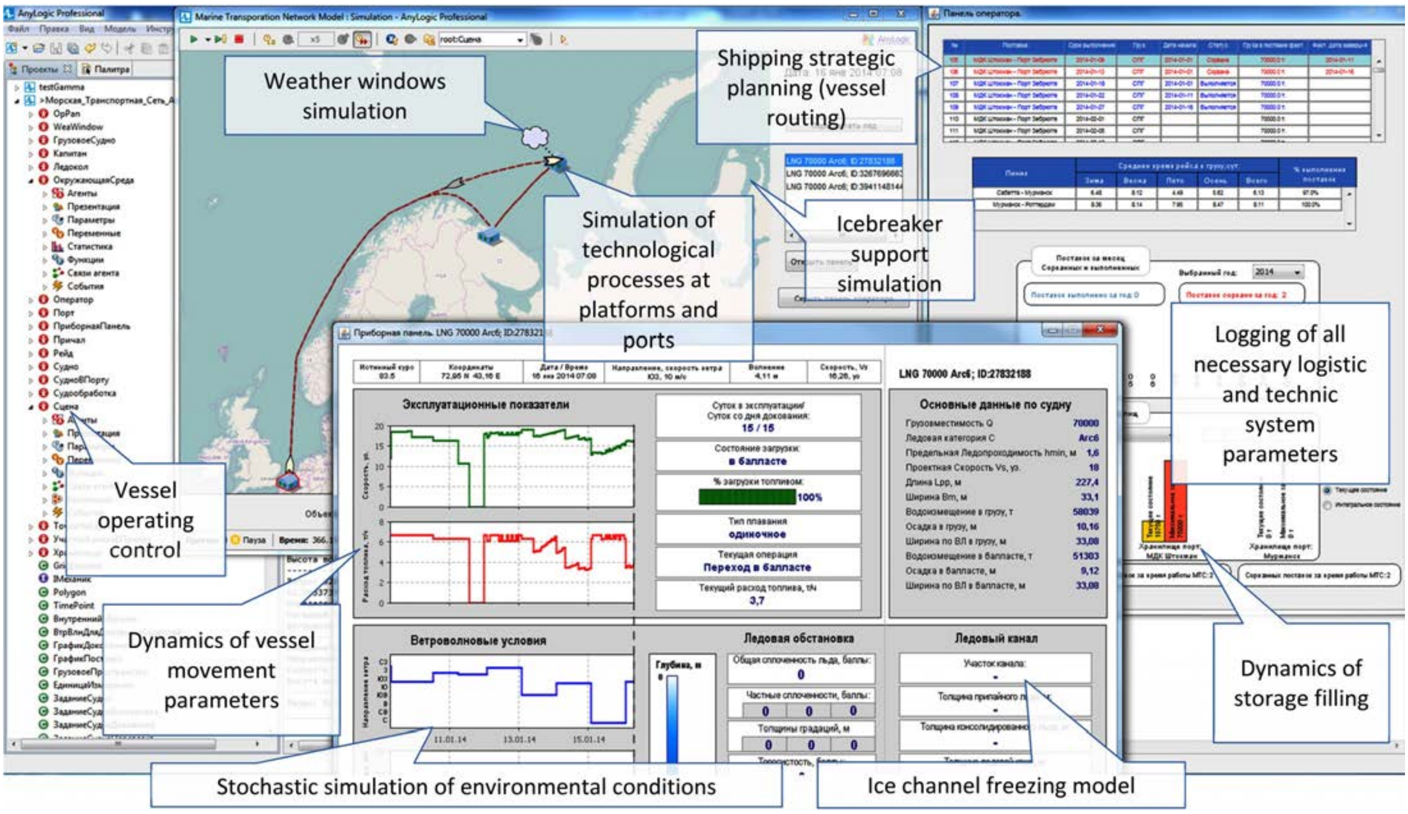

Fig.3. Agent-based simulation model of marine transport system and main simulated processes.

The agent-based MTS model also contains local "sub-models" describing detached processes of dynamic nature. A typical example of such sub-model is a model of channel freezing in fast ice. Each ship passing through an ice channel changes its characteristics, which govern the speed of the current ship as well as the speed of vessels behind. Therefore, the influence of ice channel can be precisely estimated only by a computational experiment with the entire transport system model. Depending on the concerned task any other subject-oriented sub-model (e.g., model of production processes in drilling platforms, etc.) can be implemented.

The agent-based model contains MTS planning modules at tactical and operational levels (in accordance with hierarchy given in [14]).

The tactical planning (routing) of ships is based on external computation blocks with the purpose to provide transportation of required freight volumes, scheduling of deliveries (voyages), setting of specific ships for specific trips or auxiliary non-transport operations, management of icebreaker escort operations, ship docking scheduling, etc. The tactical plan can be readily updated if it was found non-feasible at some time while running the simulation model. Tactical planning approaches are discussed in [22] in more detail. It is only to be noted here that rigorous combinatorial algorithms seem to be impractical in solving common MTS cases with typical features that are difficult to formalize (multiple ship and cargo types, transhipment points, time-dependent factors like ice voyage time, additional resources like icebreakers, etc.). For this reason, the authors focused on the application of heuristic or semi-heuristic methods to solve specific practical problems in MTS investigations rather than on the development of a universal tactical planner, which is considered as a future task.

Operational level of planning is intended to execute the tactical plan in specific circumstances, i.e. with current status of MTS objects (delayed ship arrivals, unfavourable weather conditions, actual storage filling levels, etc.). Tactical planning tasks are resolved by adjustment of ship speed, ship queuing at berths, duration and schedule of icebreaker support, etc. According to the authors' understanding, operational planning modules should be customized for specific MTS cases to take a multitude of local features into account. In this case both formal optimization algorithms and formalized versions of different expert approaches can be used.

Thus, in the frame of proposed approach, agent-based simulation model serves as the centre of multidisciplinary integration and it potentially enables to model all the aspects of MTS operation.

3. LAYOUT OF THE SOFTWARE FRAMEWORK

The software solution incorporates four closely integrated main program blocks (see Fig.4).

All MTS objects are defined and edited using the command shell "Scenario builder".

The block "Route data statistics" allows obtaining a set of statistical data on navigation parameters (voyage time, etc.) of investigated ships. It is required for further comparative analysis of the fleet configuration and fleet tactical and operational planning. It could be said, that this module logically corresponds to the task solved by "specialists in arctic voyage time estimation" (see introduction).

The most favourable configuration of MTS fleet is defined in the "Optimization block" using specialized design models, which are developed individually for each considered type of MTS (linear shipment, offshore supply, tramp shipping, etc.).

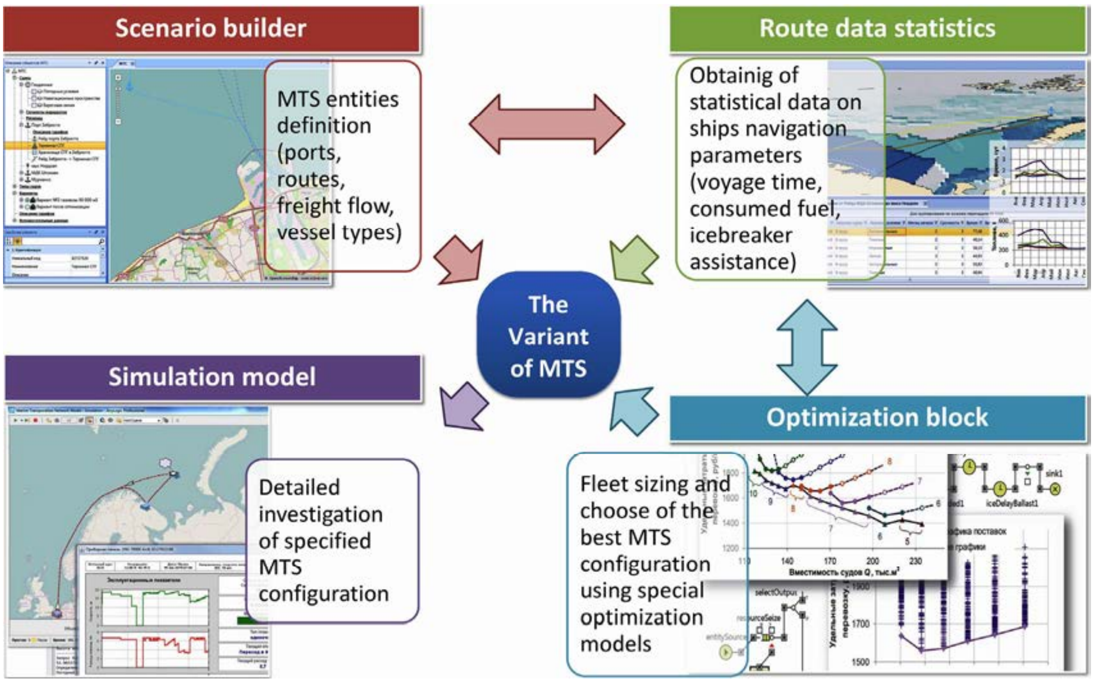

Fig.4. Layout of the software blocks for MTS investigation

Optimization modules could be developed not only to solve fleet sizing problem, but also to obtain the best ship particulars according to some criterion. These modules logically correspond to “ship design task”. The functionality of an optimization module depends on the task it solves; however, such module is detached from the simulation model and enables to obtain a certain configuration of MTS called “The Variant of MTS”. It contains full description of all the objects and can be further examined by computation experiments with an agent-based model. Actually, the Variant of MTS may contain any arbitrary MTS configuration that was set manually.

There is a model agreement problem, because two models with a different level of detail are used for optimization of fleet configuration and for further simulation of the same MTS. In an effort to solve this problem the optimization model should be relatively simple, however it should not distort key aspects of the transport system operation. As it is seen from practice, this requirement can be practically met even for quite special tasks. E.g., ref. [23] describes an event-based optimization model which allows evaluating the number and main parameters of LNG carriers taking into account the requirement or regular LNG delivery to destination ports that is rather important for this type of vessels.

It is also important to mention some typical obstacles of proposed multidisciplinary approach that should be considered at program level.

The first obstacle is the “scaling problem” of the MTS object model. In some cases, the detailed description of MTS components is essential to consider some important local parameters of the real system (e.g., mooring time). At the same time, for many design tasks the level of detail should be less (e.g. not mooring time, but time in port that includes mooring time among others) because of the lack of related information. However, once created object model is very hard to change afterwards (in both directions of increasing and decreasing level of detail) because all the program blocks correspond to a common level of detail. For this reason, authors accepted a high detailing in the software framework and provided special calculation models to fill attributes of MTS objects with typical values, i.e. not to do it manually. These models are based on a restricted amount of initial input information. E.g., special software module based on programming design pattern “factory” allows obtaining all the parameters of oil tankers, LNG and LPG carriers having only: cargo capacity, design speed, ice class, icebreaking capability and a number of setup variables. The same “Ship-factories” could be used to solve ship optimization task.

The second obstacle follows from the first one and it is “data completeness control”. The number of MTS objects and their parameters could be so large that manual input mistakes cannot be avoided. For example, ship can’t unload cargo in some port because manually-input depth near the berth has an invalid value. Therefore, a special algorithm to verify relations between objects and check the feasibility of MTS was realized.

The third problem is the problem of “data interpretation” in complex systems. Some example could be given here. When authors had been investigating one case study, it was found out that MTS performance was getting worse and worse during the period of the modelled life cycle of MTS. Great efforts were put to detect a mistake in the program code, but everything turned out much easier: docking period was erroneously set too long and ship’s hull roughness without docking rose up so high that ship speed in ice had decreased a lot. Obviously, only practical experience allows avoiding such troubles.

4. CASE STUDIES

Since the year 2014, seven practical tasks of various scope of work were carried out. Practical tasks varied from static calculations (voyage time and route statistics, preliminary vessel particulars using “Ship-factories”, etc.) up to full simulation of the system considering stochastic factors and logistics. Each time some aspects of MTS were of in-depth study according to project key points, but some factors were omitted. This allows authors to say, that every practical case of MTS investigation is non-typical and demands individual approach. Due to paper size restrictions, only a brief description of two case studies is given below.

1. *Development of operation model for the 120MW Leader-type icebreaker.* The aim was to estimate operating characteristics of the nuclear icebreaker intended for escort operations in the Eastern and Western sectors of Russian Arctic. For this purpose, the traffic of crude oil, LNG, LPG and transit cargoes over the Northern Sea Route (NSR) was estimated for optimistic, medium and pessimistic scenarios. The characteristics of arctic oil tankers and gas carriers with high ice classes were estimated and the simulation model of icebreaker operation was created. As a result, the freight traffic supported by one and two icebreakers was estimated for ice conditions of different severity. Also the annual icebreaker power distribution pattern (Fig.5) and duration of operation cycle between nuclear fuel recharge were calculated.

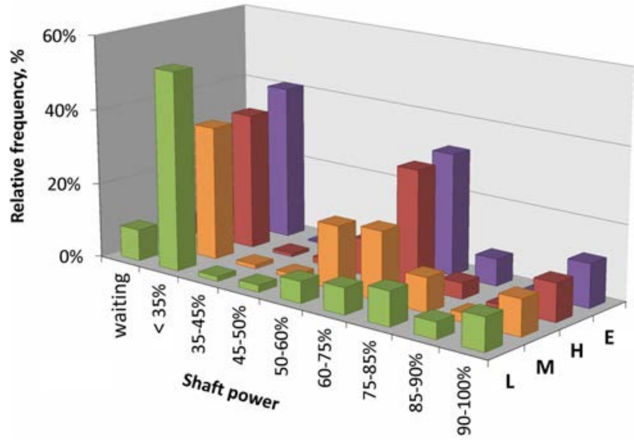

Fig. 5. Power level pattern of leader-type icebreaker over typical year of operation in light (L), medium (M), heavy (H) and extreme (E) ice conditions.

The problem of ice routing was one of the important practical tasks resolved during investigation of the Leader-type icebreaker. It is known that modern arctic vessels hardly ever sail by straight courses but use areas of weaker ice and water openings. In case of grid representation of ice environment this peculiarity should be considered but, in our case, the definition of ice routing problem differs from those given in [10, 11]. Besides the optimum route in ice, finding the optimum amount of icebreaker assistance is also required. The reason is that in some cases vessels can operate in ice either independently or under icebreaker assistance to increase speed and save fuel, however having extra costs for icebreaker services. Obviously, there is some economically proved level of icebreaker assistance with minimum costs of passage through ice covered waters.

These problems were solved using Dijkstra and A* algorithms. In case of Dijkstra algorithm ice parameters are static and a single ice chart is used for each month, but such formulation breaks the smoothness of ice conditions at joint of months, which makes it applicable only for initial route statistics calculation. During the simulation process ice conditions are interpolated between months and the problem of dynamic routing is solved by means of A* algorithm. The statement of an optimization problem of finding the optimum pathway between nodes on an oriented graph is shown in Fig.6.

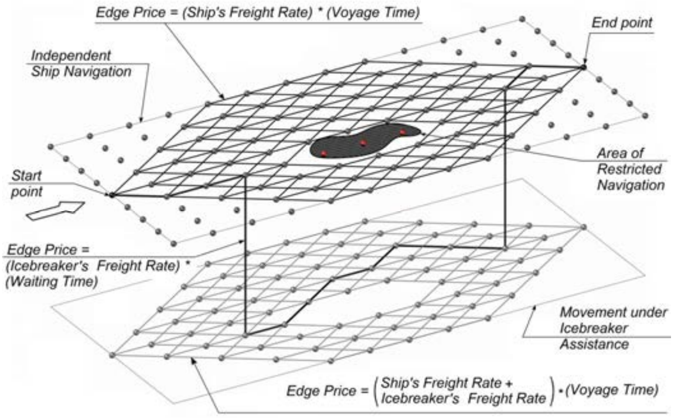

Fig.6. Ice routing problem statement.

The entire space between start and end points of the route is represented as a regular grid area. For each edge of this grid a formal passage price is determined; it is equal to the product of the vessel freight rate by the edge pass time computed by the "Mechanic" block. In addition, alternative edge price is also estimated for the case of icebreaker assisted operation considering the sum of ship's and icebreaker freight rates, as well as the convoy speed. Finally, a typical two-layer graph is obtained with one layer defining parameters of independent ship operation and the other layer defining characteristics of icebreaker assisted operation. Transition from the upper to the lower level is possible at any point; its cost is determined as a product of icebreaker waiting time (i.e. the time that the icebreaker needs to reach current point) by icebreaker freight rate. Thus, the dimension of edge price is "$ × hour", while the route is optimized by minimization of this criterion on the graph.

Fig.7 gives examples of ice routing tasks solution; calculation time on a standard PC is about a second.

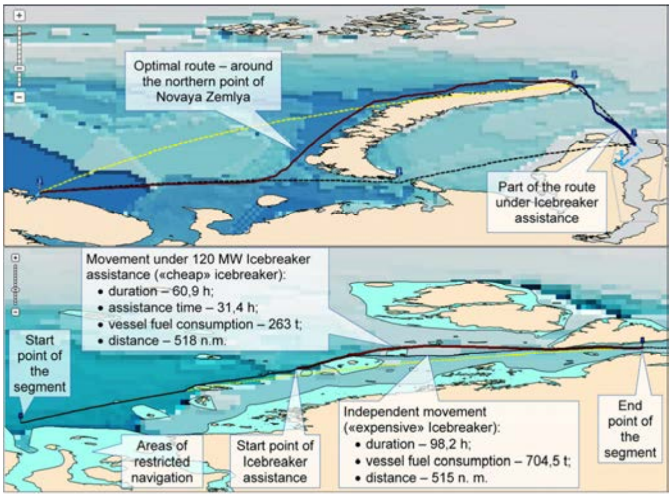

Fig.7. Practical application of ice routing techniques.

Fig.7 shows that if the relative cost of icebreaker services is low, then a ship will always require icebreaker escort, but if this cost runs high, then icebreaker assistance will be demanded only in areas where ice conditions are too severe for independent navigation. This kind of technology was used to find the required amount of icebreaker support for vessels with various ice class and also to realize the operational planning tool that allows determining the sequence of icebreaker-assisted ships.

2. *Simulation model of crude oil transportation from Novoportovskoe field (Ob' bay) to Murmansk*. A notable factor in this study was the ice channel in fast ice of Ob' bay that may reach up to 500 km in length and 2 m in ice thickness. Ice channel governed all the elements of MTS: six arctic shuttle tankers, on-shore storage and stand-by icebreaker (see Fig.8). Operation of LNG carriers of Yamal LNG project (line from Sabetta) was also considered to take into account the influence of additional ships on ice channel parameters.

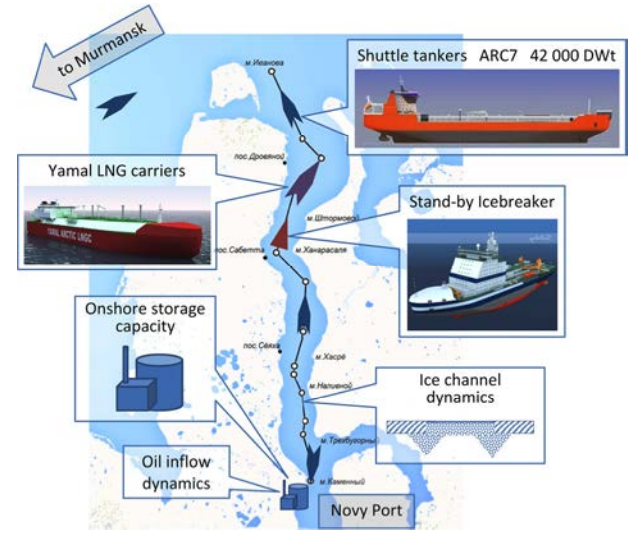

Fig.8. Ob' bay layout and objects considered in simulation model of Novy Port MTS

Project targets were:

- simulation of on-shore storage filling dynamics and estimation of its design capacity (see Fig.9);
- determination of amount and time schedule of icebreaker assistance for tankers in heavy and extreme ice conditions;
- estimation of required number of channels in fast ice and forecast dates when these channels should be laid in different ice conditions;
- assessment of the temporary transport system performance during the time period when the main tankers are not yet commissioned, and chartered vessels of small deadweight and low ice class are used for oil transportation.

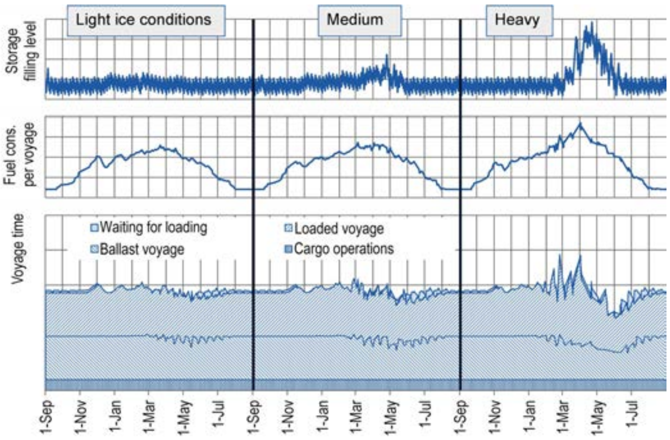

Fig.9. Annual variation of the MTS performance versus ice severity (light, medium, heavy)

These tasks were solved only through integration of ship movement model, ice channel freezing model and oil inflow model in a united program framework.

Ice channel was modelled as a sequence of separate segments; each segment has a length of 5 km and its behaviour is described by the model [24]. A simple logic condition was implemented to estimate the total number of ice channels in Ob' bay during the navigation period. A new channel was laid in case if the ship's speed in the previous channel had fallen down to 4 km. If the tanker was not able to lay a new channel due to very thick ice, then an icebreaker attended. Example of ice channel dynamics is shown in Fig.10.

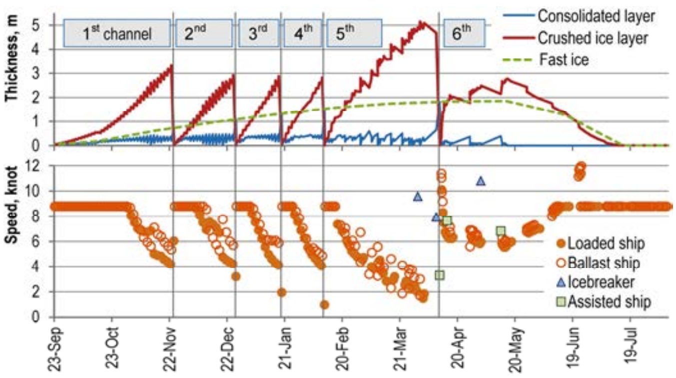

Fig.10. Parameters of ice channel segment near Novy Port in heavy ice conditions.

To provide correct tracking of how ice channel affects MTS it was also necessary to take into account the logistic factor of operational planning. However, for the first time MTS was modelled without any planning techniques. This resulted in the irregular movement of tankers because of the influence of ice channel, which is rather non-linear, but in brief it could be described so: the more time ice channel does not get renovated by ship passage, the less ship's speed in it due to thick consolidated layer. Therefore, the first ship would be overtaken by the ship that follows after, and in the end, all the ships would form a group that makes channel renovation frequency very low. As a result, storage filling level increases. After the special operational planning tool had been developed and integrated into the simulation model, vessels started to work like conveyor keeping up the constant time interval between one another. This allowed decreasing storage peak filling level approximately in two times (see Fig. 11). This example shows how the synthesis of physical and logistical algorithms could increase the level of general model adequacy.

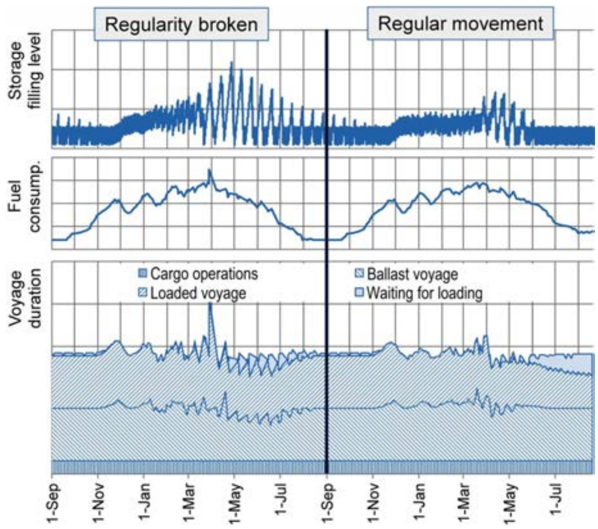

Fig.11. Influence of regularity of tanker movement on operational parameters of the system

5. CONCLUSION

Arctic MTS is a complex entity, characterized by many physical, logistical, engineering and technological aspects.

Traditional ways of MTS design and analysis in the frame of a single discipline lead to the necessity of abstracting from significant aspects relevant to other disciplines. The results obtained in this way can't properly describe the whole MTS because some factors are neglected. So, only the holistic approach, which combines models of physical and technological processes, engineering objects and logistic aspects of MTS, aspires to an adequate and consistent description of the arctic transport system.

This article describes the approach intended to provide mentioned multidisciplinary integration by means of such information technologies as geo-information systems and dynamic simulation models, based on common object-oriented program methodology. GIS environment is essential to obtain a common space, where objects of MTS interact. Agent-based simulation models allow describing the complicated logic of object behaviour and various dynamic processes inside MTS. Object-oriented program approach is required to integrate different technologies into one program framework with expandable architecture that allows accumulating various numerical techniques and algorithms relevant to MTS analysis for their further joint usage. The proposed approach is not immovable but, on the contrary, it allows the flexible configuration of MTS model to real practical tasks, considering their features and individual aspects.

A number of case studies have confirmed that the realization of multidisciplinary principles on this foundation is not only viable, but enables to investigate some aspects of MTS those other methods fail to capture.

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